

Auditing longitudinal data across institutional regimes: a graph-based compatibility protocol with evidence from Tunisia

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BSBH Foundation for Sci. Res.

Research Article

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Posted Date: September 2nd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10455680/v1>

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Additional Declarations: No competing interests reported.

Auditing longitudinal data across institutional regimes: a graph-based compatibility protocol with evidence from Tunisia

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Abstract

Longitudinal datasets often join records created under different legal, administrative, or statistical regimes. A common scale does not establish that the joined series denotes the same object or admits a valid administrative realisation. This article develops a graph-based audit that separates level registration, residual disagreement in shape, consistency of crosswalks, and feasibility of the full record. The procedure combines coordinatewise median registration, convex projection onto pre-authorised corrections, a weighted incidence decomposition, and a linear feasibility certificate. A controlled experiment distinguishes pure level shifts from changes in shape. The application uses an author-constructed quarterly panel for Tunisia from 2000Q1 to 2019Q4. The shock–transition boundary yields the largest post-registration residual in 30 of 36 registered specifications and exceeds all 33 same-design within-regime controls; conventional level diagnostics instead emphasise other boundaries. Numerical reconciliation, shape compatibility, coherent conversion, and administrative admissibility are therefore separate propositions. The audit supports accountable integration of heterogeneous records; it does not estimate a causal effect of the Tunisian transition.

Keywords: longitudinal comparability, data quality, structural change, graph consistency, public-sector data governance, Tunisia

1 Introduction

A longitudinal file may be continuous in form and discontinuous in meaning. Public records pass through constitutional change, emergency reporting, institutional redesign, changes of provider, and revisions of the population to which an administrative rule

applies. A column name may remain fixed while its legal category, sampling frame, coding rule, or permissible transformation changes. Concatenation then yields a table, not necessarily a defensible record.

This problem is not reducible to missingness or measurement error. Data quality depends on use and provenance (Wang and Strong 1996; Batini and Scannapieco 2016). Measurement-invariance analysis tests the stability of a construct across populations or occasions (Meredith 1993; Vandenberg and Lance 2000). Structural-break and change-point methods test changes in a stochastic or parametric law (Andrews 1993; Bai and Perron 1998, 2003; Killick et al. 2012); concept-drift methods examine changes in predictive relations (Gama et al. 2014). Public-sector governance adds provenance, authority, stewardship, legal purpose, and responsibility for transformations (Dawes 2010; Janssen et al. 2012; Zuiderwijk and Janssen 2014; Klievink et al. 2017; OECD 2019). These questions are related but distinct.

The present question precedes policy evaluation, forecasting, and causal design: when may records produced under successive institutional regimes be treated as one analytical object? The audit must distinguish a legitimate level conversion from disagreement in temporal shape, test whether pairwise crosswalks form a coherent system, and determine whether the reconciled numerical object can be realised as an admissible full record.

The construction uses a finite graph of regime-specific data environments. A vertex carries a local model, variable dictionary, provenance record, and full-record constraints. An edge specifies two environments and a registered comparison window. Coordinatewise median registration estimates the level crosswalk; projection onto a pre-authorised correction set admits only declared recodings or normalisations. The remaining residual measures disagreement in shape. The full system of crosswalks is then tested against the graph incidence structure, and the reconciled audit vectors are tested for a lift satisfying capacity, eligibility, confidentiality, or legal constraints. A small edge residual cannot remove a cycle inconsistency or an infeasible lift.

The graph formulation is finite-dimensional. Its connection with local-to-global methods in sheaf theory and information fusion lies in the distinction between local agreement and global exactness (Bredon 1997; Robinson 2014, 2017); the calculations use matrices, convex sets, residual vectors, and signed cycle sums. The method contributes an ordered audit rather than a composite quality score. It records level translation, residual shape disagreement, graph consistency, full-record feasibility, decision margins, provenance, and responsibility as separate objects.

The application concerns Tunisia from 2000Q1 to 2019Q4. The case combines a sharp political rupture and a constitution-making transition with source families of different frequencies and constructions. The deposited panel is author-constructed and source-aligned, not provider-native quarterly microdata. The analysis therefore concerns the internal compatibility of the deposited record; it does not reconstruct every provider-to-quarter transformation.

Under the registered historical windows, the post-registration residuals are 0.102, 0.209, and 0.147 for the pre-shock, shock-transition, and transition-post boundaries. Shock-transition is largest in 30 of 36 degree-ridge-correction specifications and exceeds all 33 same-design within-regime controls. Simple level diagnostics instead make the

pre-shock and transition-post boundaries at least as prominent. The distinction is substantive: the shock-transition boundary is exceptional in the disagreement that remains after a registered conversion.

Sections 2–4 define the method and its guarantees; Sections 5–6 give the research design and evidence; Section 7 states the administrative protocol. Proofs, counterexamples, and the consistency extension appear in Online Resource 1. Online Resource 2 contains the anonymised computational archive.

2 Related methods and the methodological gap

2.1 Data quality, provenance, and fitness for use

The influential data-quality literature rejects the view that accuracy alone determines usefulness. Completeness, timeliness, consistency, interpretability, and accessibility matter because data are consumed in institutional settings (Wang and Strong 1996; Batini and Scannapieco 2016). Public-sector scholarship adds a stewardship problem: authorities must be able to state who created a record, which transformation was permitted, and who accepted responsibility for reuse (Dawes 2010; OECD 2019). FAIR practice and formal provenance standards strengthen this demand by treating data lineage as a first-class part of a reusable object (Wilkinson et al. 2016; Moreau and Missier 2013).

These approaches establish why provenance and documentation are necessary. They do not, by themselves, supply a mathematical decomposition of inter-regime disagreement. A source may be fully documented and still be unsuitable for pooling. Conversely, a pair of numerical series may be easily reconciled while the underlying administrative records remain incompatible. The present method therefore treats provenance and numerical fit as separate coordinates of a decision rather than combining them into a single quality score.

2.2 Measurement invariance and structural change

Measurement invariance is a logical prerequisite for comparing latent constructs across groups or occasions (Meredith 1993; Vandenberg and Lance 2000). Where an explicit factor model and item-level observations are available, invariance analysis is more informative than the method proposed here. It can identify which loadings, intercepts, or residual variances fail to remain stable. The present problem is different. Public data warehouses frequently combine already-constructed indicators, event counts, administrative variables, and hand-coded institutional records for which a common latent-variable model is neither available nor defensible. The audit operates at the level of the declared analysis vector and therefore cannot replace an item-level invariance study.

Structural-break methods are similarly indispensable when the target is a change in regression parameters, moments, or error distributions (Andrews 1993; Bai and Perron 1998, 2003). Change-point procedures can estimate the location and number of breaks under explicit probabilistic assumptions (Killick et al. 2012). The method developed below does not compete with that task. Its boundary dates are institutional hypotheses

fixed before the audit; the question is whether the records adjoining those dates can be reconciled under a declared conversion. A structural break may be substantively real and still admit a legitimate crosswalk. Equally, a small statistical break may conceal a legal or semantic incompatibility.

2.3 Local-to-global data integration

Graph and sheaf approaches represent heterogeneous local observations together with maps that express how they should agree (Robinson 2014, 2017). Their principal advantage is conceptual economy: local consistency, global exactness, and obstruction live in one architecture. This article adopts that distinction but specialises it to an auditable policy-data problem. The graph vertices are regime-specific records, the edge maps are registered conversions, and the cycle component records a failure of global conversion consistency. The specialisation matters because policy data require a second obstruction that ordinary vector-space agreement does not capture: a numerical section may fail to lift to a legally and administratively admissible record.

2.4 The gap

The missing element is not another generic harmonisation score, but an ordered procedure that answers the following questions:

- (i) what part of an inter-regime difference is an admissible level conversion;
- (ii) what disagreement remains after that conversion and any authorised bounded correction;
- (iii) whether the complete set of conversions is globally coherent;
- (iv) whether the numerically reconciled object can be realised by full records; and
- (v) whether the evidence supports pooling, review, or separation under a registered loss or quality rule.

The procedure is modular. Richer data may justify another local model, translation estimator, or decision rule without altering the separation of these stages.

Registered compatibility audit: from regime records to an accountable disposition

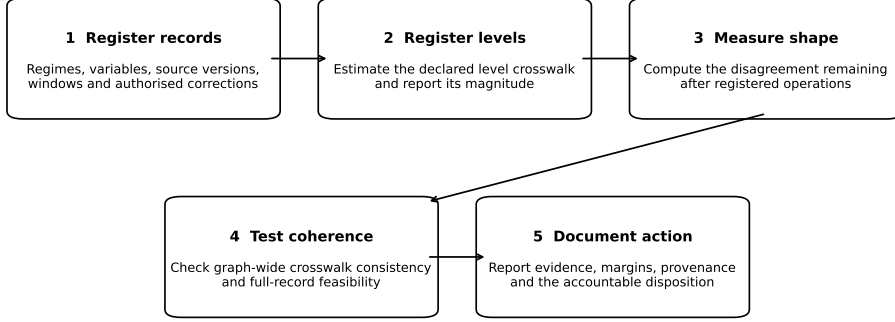


Fig. 1 Registered compatibility audit from regime-specific records to an accountable disposition. The stages are ordered: later diagnostics do not retrospectively alter the variables, windows, or authorised corrections registered at the outset

3 Formal audit framework

3.1 Regime graph and local records

Let $G = (V, E)$ be a finite connected graph with an arbitrary orientation. A vertex $i \in V$ represents a regime-specific data environment. It carries a finite fitting set S_i , a declared evaluation domain $T_i \supseteq S_i$, observations $y_i : S_i \rightarrow \mathbb{R}^p$, a fitted record $f_i : T_i \rightarrow \mathbb{R}^p$, a full-record feasible set $\mathcal{K}_i \subset \mathbb{R}^{r_i}$, and an audit projection $P_i : \mathbb{R}^{r_i} \rightarrow \mathbb{R}^p$. An oriented edge $e = (i, j)$ declares an audit window $Q_e \subset T_i \cap T_j$ on which both fitted records are defined. This distinction permits a short local fitting set while making every extrapolated comparison explicit in the registered evaluation domain.

Definition 3.1 (Regime audit datum) A regime audit datum is

$$\mathfrak{A} = (G, \{S_i, T_i, y_i, f_i, P_i, \mathcal{K}_i\}_{i \in V}, \{Q_e, C_e, w_e\}_{e \in E}),$$

where $C_e \subset \mathbb{R}^p$ is a non-empty compact convex set of authorised constant corrections and $w_e > 0$ is an edge weight. The datum is *registered* when the fitting sets, evaluation domains, variables, edge windows, estimators, correction sets, controls, and decision tolerances are fixed before the reported residuals are inspected.

The fitted record may be produced by any declared estimator. In the empirical application it is a ridge-regularised polynomial. For a chart with observations $Y \in \mathbb{R}^{n \times p}$ and design matrix $X \in \mathbb{R}^{n \times (d+1)}$, the coefficient matrix is

$$\hat{\Theta} = \arg \min_{\Theta \in \mathbb{R}^{(d+1) \times p}} \left\{ \|Y - X\Theta\|_F^2 + \lambda \|R\Theta\|_F^2 \right\}, \quad (1)$$

where $R = \text{diag}(0, 1, \dots, 1)$ leaves the intercept unpenalised.

Table 1 Core notation for the compatibility audit

Symbol	Meaning
S_i, T_i	fitting set and declared evaluation domain of regime i
y_i, f_i	observed and fitted p -dimensional records
Q_e	registered comparison window for edge $e = (i, j)$
$\hat{a}_e$	robust constant level translation
$C_e, \hat{c}_e$	authorised correction set and its fitted correction
D_e	post-registration residual shape disagreement
B, W, h	incidence matrix, edge weights, and cycle component
x, z, P_i	full record, audited vector, and audit projection
$\mathcal{D}_e$	registered administrative disposition
T_L, T_H, P_L, P_H	lower/upper numerical and control-percentile criteria

Proposition 3.2 (Unique local fit) *If $\lambda > 0$ and the intercept column of X is non-zero, the criterion in (1) is strictly convex on the identifiable coefficient space and has the unique minimiser*

$$\hat{\Theta} = (X^\top X + \lambda R^\top R)^{-1} X^\top Y.$$

The proposition guarantees a reproducible computation; it does not create information. A two-quarter chart remains a two-quarter chart, and regularisation must not be described as identification of a crisis law.

3.2 Level registration and residual shape disagreement

For $e = (i, j)$ define the unregistered edge defect

$$\Delta_e(q) = f_j(q) - f_i(q), \quad q \in Q_e.$$

A constant translation $a_e \in \mathbb{R}^p$ represents a level crosswalk. The baseline translation is chosen by coordinatewise L^1 minimisation:

$$\hat{a}_e \in \arg \min_{a \in \mathbb{R}^p} \sum_{q \in Q_e} \|\Delta_e(q) - a\|_1. \quad (2)$$

Proposition 3.3 (Robust registration) *The solution set of (2) is the Cartesian product of the coordinatewise median intervals of $\{\Delta_e(q) : q \in Q_e\}$. If each coordinate has a unique sample median, $\hat{a}_e$ is unique.*

Set $r_e(q) = \Delta_e(q) - \hat{a}_e$. The authorised correction is constant on the audit window and belongs to C_e . In the application,

$$C_e = \prod_{k=1}^p [-\rho s_{e,k}, \rho s_{e,k}], \quad s_{e,k}^2 = |Q_e|^{-1} \sum_{q \in Q_e} r_{e,k}(q)^2,$$

where ρ is registered in advance. The correction solves

$$\hat{c}_e = \arg \min_{c \in C_e} \frac{1}{|Q_e|} \sum_{q \in Q_e} \|r_e(q) - c\|_2^2. \quad (3)$$

The edge residual is

$$D_e = \left(\frac{1}{p|Q_e|} \sum_{q \in Q_e} \|r_e(q) - \hat{c}_e\|_2^2 \right)^{1/2}. \quad (4)$$

The term “correction” is used narrowly: it denotes a pre-authorised coding or normalisation allowance. It does not denote a discretionary change to the historical series.

Theorem 3.4 (Explicit bounded correction) *Let $\bar{r}_e = |Q_e|^{-1} \sum_{q \in Q_e} r_e(q)$. The unique solution of (3) is the Euclidean projection*

$$\hat{c}_e = \Pi_{C_e}(\bar{r}_e).$$

For a box $C_e = \prod_k [-b_{e,k}, b_{e,k}]$, this is the coordinatewise clipping rule

$$\hat{c}_{e,k} = \min\{b_{e,k}, \max\{-b_{e,k}, \bar{r}_{e,k}\}\}.$$

Moreover, Π_{C_e} is non-expansive.

The separation of $\hat{a}_e$ and D_e is essential. A large translation with a small residual describes a level change that is well represented by the registered crosswalk. A small translation with a large residual describes a change in shape that a constant crosswalk cannot absorb. Reporting only the raw root-mean-square difference confounds the two.

3.3 Global consistency of edge translations

Pairwise crosswalks need not form a coherent system. Let $m = |E|$, $n = |V|$, and let $B \in \mathbb{R}^{m \times n}$ be the oriented incidence matrix: the row for $e = (i, j)$ has -1 in column i , $+1$ in column j , and zero elsewhere. Stack the edge translations in $a \in \mathbb{R}^{m \times p}$ and let $W = \text{diag}(w_e)$. A system of vertex offsets $g \in \mathbb{R}^{n \times p}$ induces exact edge translations Bg .

The closest globally exact system is obtained from

$$\hat{g} \in \arg \min_{g: \sum_i g_i = 0} \|W^{1/2}(a - Bg)\|_F^2. \quad (5)$$

Because G is connected, the normalisation in (5) removes the common-offset indeterminacy and makes $\hat{g}$ unique.

Theorem 3.5 (Weighted exact-cycle decomposition) *For every $a \in \mathbb{R}^{m \times p}$ there is a unique decomposition*

$$a = B\hat{g} + h, \quad B^\top W h = 0, \quad (6)$$

with $\sum_i \widehat{g}_i = 0$. The two terms are orthogonal in the weighted inner product. The following statements are equivalent:

- (a) $h = 0$;
- (b) there exist vertex offsets g_i such that $a_e = g_j - g_i$ on every edge;
- (c) the signed sum of a_e around every cycle of G is zero.

If G is a tree, every edge-translation system is exact.

The theorem separates two kinds of failure. A chronological chain has no cycle obstruction, yet its neighbouring records can have large shape residuals. A multi-agency network may have small edge residuals and nevertheless possess a non-zero cycle component. The latter means that the conversion obtained by travelling through one sequence of agencies differs from the conversion obtained through another.

3.4 Full-record lift and its dual obstruction

The audit vector is rarely the whole record. Let $x_i \in \mathbb{R}^{r_i}$ denote the full record at vertex i . Suppose the vertex constraints are polyhedral,

$$A_i x_i \leq b_i, \quad P_i x_i = z_i,$$

and the full overlap relations are linear,

$$L_e x_i - R_e x_j = 0, \quad e = (i, j).$$

After stacking all variables, these conditions can be written

$$Ax \leq b, \quad Ex = h(z). \tag{7}$$

Here $h(z)$ incorporates the audited vectors and the edge relations.

Theorem 3.6 (Full-record feasibility certificate) *The audited vectors z admit a full-record lift satisfying (7) if and only if there is no pair (λ, y) such that*

$$\lambda \geq 0, \quad A^\top \lambda + E^\top y = 0, \quad \lambda^\top b + y^\top h(z) < 0. \tag{8}$$

Any pair satisfying (8) is a verifiable certificate that numerical agreement cannot be realised by an admissible full record.

The practical force of Theorem 3.6 is that administrative incompatibility need not be represented by an informal warning. Where the relevant rules are linear or can be conservatively linearised, the failure can be accompanied by a dual certificate. Online Resource 1 gives a two-programme capacity example in which the audited totals agree exactly while the full record is infeasible.

Example 3.7 (Two obstructions that edge residuals do not detect) Consider three regime vertices with scalar translations $a_{12} = 1$, $a_{23} = 1$, and $a_{13} = 1$. Each edge translation is individually well defined, but the signed cycle sum $a_{12} + a_{23} - a_{13} = 1$ is non-zero; hence no system of vertex offsets generates all three conversions. Separately, let a reconciled total require $x_1 + x_2 = 1$ while the admissible full record satisfies $0 \leq x_1 \leq 0.4$ and $0 \leq x_2 \leq 0.4$. The numerical total has no lift. In the notation of Theorem 3.6, take the multipliers on the two upper bounds equal to one, the multipliers on the lower bounds equal to zero, and $y = -1$. Then $A^\top \lambda + E^\top y = 0$ and $\lambda^\top b + y^\top h(z) = 0.8 - 1 < 0$. Thus a cycle inconsistency and a full-record impossibility can both remain invisible to an edge residual taken alone.

3.5 Decision rule

Let p_e denote the strict percentile of D_e in a declared within-regime control design, and let $m_e \in \{0, 1\}$ flag a hard legal, semantic, eligibility, or confidentiality incompatibility. Let $T_L < T_H$ be numerical tolerances and $P_L < P_H$ control percentiles. The illustrative action rule is

$$\mathcal{D}_e = \begin{cases} \text{keep separate,} & m_e = 1 \text{ or } D_e > T_H \text{ or } p_e > P_H, \\ \text{review before pooling,} & D_e \geq T_L \text{ or } p_e \geq P_L, \\ \text{conditional pooling,} & \text{otherwise.} \end{cases} \quad (9)$$

The calligraphic symbol $\mathcal{D}_e$ denotes a disposition and is distinct from the numerical residual D_e . The rule is not a statistical test. It converts registered numerical and documentary evidence into an accountable disposition. Its tolerances must be tied to institutional loss, quality standards, or legal requirements in a production application.

4 Mathematical properties of the integrated audit

Ridge regression, medians, projections, graph incidence, and linear feasibility are standard. Their ordered composition separates the obstructions detected by the audit. The following results establish the properties required for that use.

4.1 Deterministic perturbation bounds

For an edge e , regard the translated defect r_e as an element of the Hilbert space $H_e = (\mathbb{R}^p)^{Q_e}$ with the normalised Euclidean norm. Constant corrections in C_e are embedded diagonally in H_e . The distance in (4) is then the distance from r_e to the embedded correction set, divided by $\sqrt{p}$.

Theorem 4.1 (Stability of correction and residual) *Let $r, \tilde{r} \in H_e$ and let $C, \tilde{C} \subset \mathbb{R}^p$ be non-empty compact convex correction sets, embedded as constant functions. Then*

$$\left\| \Pi_C(\tilde{r}) - \Pi_C(r) \right\|_2 \leq \left\| \tilde{r} - r \right\|_2, \quad (10)$$

$$\left| \text{dist}(r, C) - \text{dist}(\tilde{r}, \tilde{C}) \right| \leq \|r - \tilde{r}\|_{H_e} + d_H(C, \tilde{C}), \quad (11)$$

where d_H is the Hausdorff distance. For the graph problem, if a and $\tilde{a}$ are two edge-translation systems on the same weighted graph, their cycle components satisfy

$$\|h(a) - h(\tilde{a})\|_W \leq \|a - \tilde{a}\|_W.$$

The theorem gives a finite-sample error budget. A change in the data affects the residual by at most the change in the translated defect; a change in the authorised correction set enters through its Hausdorff distance. The cycle projection is likewise non-expansive. These bounds do not require a distributional approximation.

4.2 Decision margins

A governance decision should not change because the sixth decimal place has moved. Define the numerical margin of an edge by its distance from the active thresholds. The metadata flag is treated separately because a hard incompatibility is not a numerical quantity.

Theorem 4.2 (Margin stability of the disposition) *Suppose $m_e = 0$. Let $\tilde{D}_e$ and $\tilde{p}_e$ satisfy*

$$|\tilde{D}_e - D_e| \leq \varepsilon_D, \quad |\tilde{p}_e - p_e| \leq \varepsilon_p.$$

If D_e is farther than ε_D from T_L and T_H , and p_e is farther than ε_p from P_L and P_H , then the action in (9) is unchanged. The rule is monotone: increasing D_e , p_e , or m_e cannot move the action towards a less cautious category.

This result has a simple operational implication. A report should disclose the distance from the decision thresholds, not only the category. Where the margin is small, the correct disposition is sensitivity analysis rather than rhetorical certainty.

4.3 Level and shape are not substitutes

The purpose of median registration can be seen in a deterministic linear example. Suppose on a symmetric audit grid $t_1, \dots, t_N$ with mean zero,

$$f_i(t) = \alpha + \beta t, \quad f_j(t) = \alpha + \delta + (\beta + \kappa)t.$$

With no correction set, the exact median translation is δ when the grid is symmetric, and

$$D_e = \frac{\|\kappa\|_2}{\sqrt{p}} \left(N^{-1} \sum_{q=1}^N t_q^2 \right)^{1/2}. \quad (12)$$

Thus a pure level shift ($\kappa = 0$) can be arbitrarily large while the post-registration residual is zero. A pure shape shift ($\delta = 0$, $\kappa \neq 0$) cannot be removed by a constant translation. The controlled simulation in Section 5.5 adds noise and confirms this algebraic separation.

Algorithm 1 Registered compatibility audit

Require: Regime graph G ; versioned local records; audit projections; edge windows; authorised correction sets; control design; decision registry.

- 1: Register the regimes, variables, source versions, windows, local estimators, correction sets, and tolerances.
 - 2: Fit the declared local record on each vertex and record model adequacy and short-window flags.
 - 3: **for** each oriented edge $e = (i, j)$ **do**
 - 4: Compute the fitted edge defect Δ_e and the componentwise median translation $\hat{a}_e$.
 - 5: Project the translated mean defect onto the authorised set to obtain $\hat{c}_e$.
 - 6: Compute the post-registration residual D_e and its coordinate decomposition.
 - 7: Compare D_e with same-design within-regime controls and registered model sensitivities.
 - 8: **end for**
 - 9: Project the complete translation system onto $\text{im } B$ and report the cycle component.
 - 10: Test the full-record constraints; where infeasible, retain a dual certificate.
 - 11: Apply the registered decision rule, report the decision margin, and assign documentary sign-off.
-

4.4 Scope of the guarantees

The formal results are conditional on the registered audit datum. They do not establish that the chosen variables are substantively sufficient, that the local model is correctly specified, or that the upstream data construction is valid. Those are separate empirical and documentary claims. The mathematics instead guarantees that, conditional on the declared inputs, the calculation has a unique meaning, exposes the cycle component, provides a feasibility test, and yields a decision whose stability can be assessed.

4.5 Registered audit algorithm

Algorithm 1 states the order of operations. The order is substantive: later stages must not be used to retroactively redefine the variables, windows, or permitted corrections that generated an inconvenient result.

5 Research design and Tunisian application

5.1 Why Tunisia is an informative case

Tunisia provides a stringent, not representative, application. The 2010–2011 uprising and the fall of the Ben Ali regime were followed by constitution-making, competitive political reorganisation, and later consolidation (Murphy 2011; Stepan 2012; Bellin 2012; Haugbølle and Cavatorta 2011). The 2014 Constitution and the National Dialogue period provide further institutional anchors (Constitute Project 2014; Norwegian Nobel Committee 2015).

The boundaries are historically fixed rather than estimated from the audited series. The source families also differ in native frequency: survey waves, annual governance indicators, event data, macroeconomic series, and dated institutional records. Long pre- and post-transition spans permit within-regime pseudo-boundaries, while the incomplete provider-to-quarter mapping makes the provenance limit explicit. The application is computationally reproducible from the deposited aligned file, but not yet independently reconstructible from every provider-native release.

The boundary residuals are not causal effects of the revolution, the constitution, or a policy intervention, and they do not rank institutional welfare. The dates identify record environments, not treatments.

5.2 Data and provenance

The source-aligned panel contains 80 quarters from 2000Q1 to 2019Q4 and 17 deposited fields. The audit uses three coordinates on $[0, 1]$: institutional trust/governance, crisis stress, and visible institutional or policy response. Source families include Arab Barometer, V-Dem, the Worldwide Governance Indicators, ACLED, the World Development Indicators, and a dated institutional chronology (Arab Barometer 2026; V-Dem Institute 2026; World Bank 2026b; Armed Conflict Location and Event Data Project 2026; World Bank 2026a). The coordinates are author-constructed planning variables, not provider-native quarterly observations or latent-trait estimates.

The computational input is an exact six-column projection of the 17-column panel: quarter, decimal year, the three audit coordinates, and a zero-based row index. The projection involves no digitisation, interpolation, estimation, or rounding and is verified before the empirical workflow runs.

The upstream construction is only partly reconstructible. Some provider files cannot be redistributed under their licences; complete reconstruction would require the native releases, observation dates, mapping rules, normalisation versions, component weights, and manual-coding flags. Table 2 states this evidential boundary.

For this reason, the empirical application audits the deposited source-aligned quarterly panel as a record object. It is not presented as a validation of the complete upstream construction chain.

5.3 Registered charts and audit windows

Four historical charts are used. The pre-regime chart covers 2000Q1–2010Q3. The shock chart covers 2010Q4–2011Q1 and contains only two quarters. The transition chart covers 2011Q2–2014Q4. The post-transition chart covers 2015Q1–2019Q4. The three audit windows are 2010Q1–2011Q2, 2010Q4–2012Q2, and 2014Q1–2015Q4. The originally registered historical reference uses quadratic ridge fits with $\lambda = 1$, but it is not treated as identification of a crisis process. A linear fit on the same windows and a linear fit with an extended four-quarter shock chart are reported as conservative co-primary checks. Weaker and stronger ridge penalties and the extended-window quadratic fit complete the registered sensitivity set. The empirical claim concerns the stability of the boundary ordering across these choices, not the point estimate from a two-observation quadratic chart.

Table 2 Construction ledger for the three deposited audit coordinates

Field	Principal source families and native frequency	Deposited representation	Declared upstream limitation and interpretation
<code>trust_obs</code>	Arab Barometer (survey waves); V-Dem v16 and WGI (annual)	Exact field in the 17-column panel; $[0, 1]$, larger values denote stronger trust/governance	Release identifiers, quarter assignments, normalisation formulae, and weights are incomplete in the mapping ledger. Descriptive audit coordinate, not a latent-trait estimate or causal outcome.
<code>shock_obs</code>	ACLED (events); WDI and dated chronology (annual, periodic, or event-based)	Exact field in the 17-column panel; $[0, 1]$, larger values denote greater crisis stress	Event-to-quarter and annual-to-quarter construction is not independently validated in this release. Composite planning-stress coordinate, not a structural-shock estimate.
<code>policy_proxy</code>	Dated institutional chronology and international reports (irregular events)	Exact field in the 17-column panel; $[0, 1]$, larger values denote more visible institutional activity	Event anchors are deposited, but provider-specific transformations and manual-coding sign-off are incomplete. Visibility proxy, not a welfare or effectiveness ranking.

Note: unavailable transformation details are recorded as audit limitations rather than inferred. Online Resource 2 contains the source manifest, proxy dictionary, exact 17-to-6-column projection check, and provider-to-quarter mapping template.

The translation is the componentwise median. The correction box permits a constant adjustment no larger than 15 per cent of the translated component root-mean-square value. The registered grid contains two polynomial degrees, three ridge penalties, and six correction fractions, producing 36 specifications. The random seed for the circular block resampling is 20260714.

5.4 Controls and benchmark diagnostics

The analysis keeps three designs distinct. Historical-window residuals answer the question posed by the institutional chronology. A separate control design places 33 within-regime pseudo-boundaries and the three actual boundaries on identical windows: eight quarters on each side, quadratic ridge fits, and a six-quarter audit span. This design prevents window length from being mistaken for unusualness. The common-window records are also compared by the Euclidean mean shift, median shift, covariance-difference Frobenius norm, and raw root-mean-square discrepancy. Each statistic describes a different feature of the boundary.

5.5 Controlled discrimination experiment

A Monte Carlo experiment tests the distinction in (12). Each replication contains two eight-point, three-coordinate records on a symmetric grid. The four cases are no break, a level shift, a shape shift, and both shifts. Gaussian noise has standard deviation 0.02, 0.05, or 0.10; each cell contains 1,000 replications. Online Resource 2 records the parameters, seed 20260722, and all draws.

The experiment checks the decomposition; it does not calibrate the Tunisian thresholds. At noise 0.05, the median post-registration residual is 0.065 under no break,

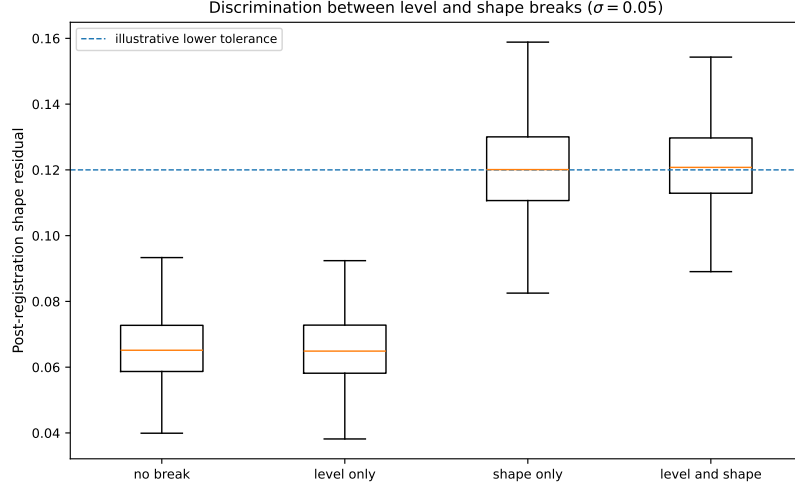


Fig. 2 Controlled discrimination between level and shape breaks at noise standard deviation 0.05. The dashed line is the illustrative lower tolerance used in the empirical decision registry, not a universal statistical cut-off

0.065 under a pure level break, 0.120 under a pure shape break, and 0.121 under both. At noise 0.10, the no-break median is 0.131. A fixed numerical tolerance therefore has no universal interpretation.

6 Results

6.1 The aligned panel and baseline historical windows

Figure 3 displays the three audit coordinates. It should be read as a description of the input to the compatibility analysis, not as a causal chronology. The visible discontinuities motivate the registered boundaries, but the results depend on fitted chart comparisons rather than pointwise inspection.

Table 3 reports the historical-window audit. The raw root-mean-square differences are 0.316, 0.353, and 0.230. Median registration reduces them to 0.102, 0.210, and 0.149. The bounded correction has little further effect: the final residuals are 0.102, 0.209, and 0.147. This small incremental change is useful evidence. The main result is not created by the 15 per cent correction allowance.

The translation norms are 0.518, 0.497, and 0.332. The pre-shock boundary therefore combines a large level conversion with a comparatively modest shape residual. The shock-transition boundary combines a substantial conversion with the largest remaining disagreement. The transition-post boundary has a smaller translation but a residual between the other two. A single raw discrepancy would obscure these distinctions.

The resampling intervals in Table 3 are sensitivity bands, not treatment-effect confidence intervals. The windows contain only six to eight quarters, and the circular

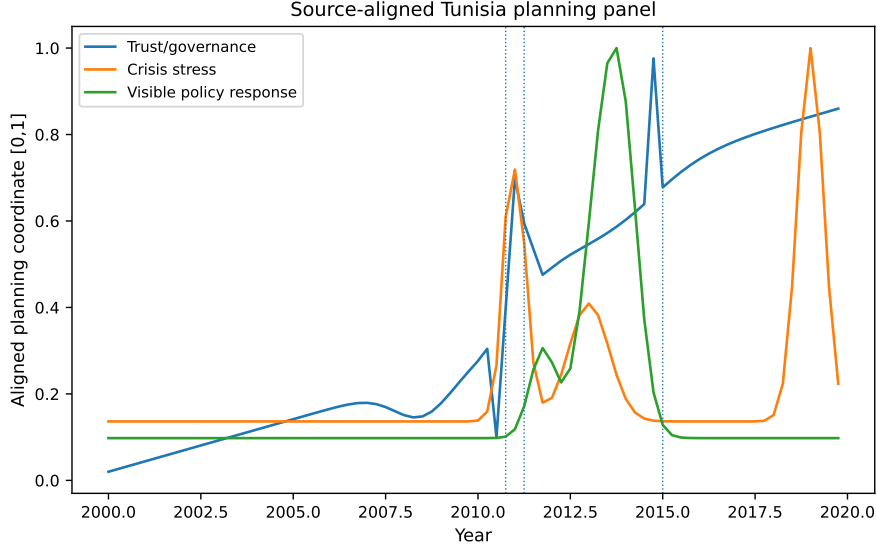


Fig. 3 Source-aligned quarterly planning coordinates for Tunisia, 2000Q1–2019Q4. These are author-constructed analysis coordinates, not provider-native quarterly series

two-quarter block design cannot justify conventional asymptotic inference. The leave-one-quarter ranges are therefore reported alongside them. The shock–transition residual remains the largest throughout its deletion range.

6.2 Level–shape decomposition and benchmark comparison

The common-window comparison sharpens the interpretation. Figure 4 plots the translation norm against the post-registration shape residual for the actual boundaries and 33 within-regime controls. The three actual boundaries occupy the upper or right-hand region, but in different ways. Pre–shock has the largest translation. Shock–transition has the largest shape residual. Transition–post has a large level shift under the conventional mean and median diagnostics, yet its shape residual is below that of shock–transition.

Table 4 reports strict finite-sample ranks. Shock–transition is the only actual boundary above every control on the shape residual. Pre–shock and transition–post are above every control on simple mean and median shifts. The covariance difference is less exceptional for all three. The result is not that the proposed residual is universally superior. Rather, it identifies a form of incompatibility that level statistics do not isolate.

6.3 Registered specification grid

Across the 36 degree–ridge–correction specifications, shock–transition is the largest residual in 30 cases and transition–post in six. Pre–shock is never the largest. Absolute magnitudes vary materially. Under a strong ridge penalty, all three residuals decline;

Table 3 Registered historical-window audit

Boundary	Audit window	Raw RMS	After level registration	Final residual	$\ \widehat{a}_e\ _2$
pre-shock	2010Q1–2011Q2 ($n = 6$)	0.316	0.102	0.102	0.518
shock-transition	2010Q4–2012Q2 ($n = 7$)	0.353	0.210	0.209	0.497
transition-post	2014Q1–2015Q4 ($n = 8$)	0.230	0.149	0.147	0.332

Boundary	Circular-block sensitivity band	Leave-one-quarter-out range
pre-shock	[0.030, 0.146]	[0.084, 0.111]
shock-transition	[0.076, 0.294]	[0.170, 0.225]
transition-post	[0.049, 0.198]	[0.117, 0.160]

Notes: Raw RMS is calculated before level registration. After level registration is the residual after the componentwise-median translation and before the bounded correction. Final residual is D_e after the authorised correction. The sensitivity band is the 2.5–97.5 percentile interval from the registered circular block calculation.

Table 4 Common-window actual-boundary diagnostics and strict ranks among 33 within-regime controls

Boundary	Translation	Rank	Shape residual	Rank	Mean shift	Rank
pre-shock	0.652	100.0	0.251	93.9	0.407	100.0
shock-transition	0.321	100.0	0.438	100.0	0.304	90.9
transition-post	0.271	97.0	0.372	97.0	0.597	100.0

Note: ranks are percentages of controls strictly below the actual value; 100.0 means “above all 33 controls”, not $p = 0$.

under a weak penalty, they increase. The short shock chart is therefore a genuine source of uncertainty. The relative prominence of shock-transition is more stable than its exact value.

Table 5 isolates the specification choices most directly related to the two-quarter shock chart. The shock-transition residual remains the largest under the linear same-window fit and under the extended linear shock chart. The magnitude, however, changes enough to preclude a claim that one local polynomial has recovered a crisis law. The extended quadratic specification is deliberately permissive: its large residual records the sensitivity of short-regime extrapolation to curvature and is interpreted as a stress check, not as a preferred local model.

The correction fraction is not influential over the registered range. Figure 6 is nearly flat because the translated mean defects are small relative to the componentwise bounds. This guards against an interpretation in which the result is manufactured by a generous adjustment allowance.

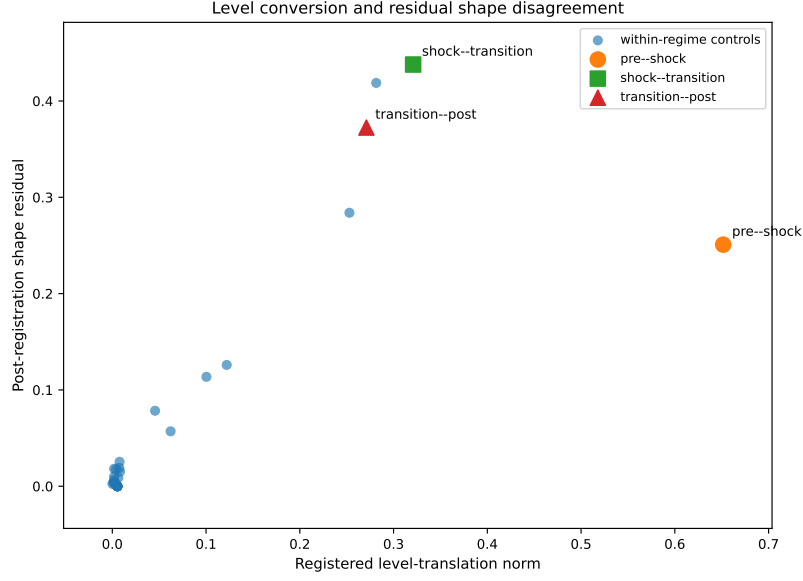


Fig. 4 Common-window separation of registered level conversion and post-registration shape incompatibility. Actual boundaries are compared with 33 same-design within-regime controls

Table 5 Short-shock and model-form sensitivity

Specification	pre--shock	shock--transition	transition--post
Registered quadratic, two-quarter shock	0.102	0.209	0.147
Linear, two-quarter shock	0.100	0.115	0.069
Linear, extended four-quarter shock	0.157	0.179	0.069
Quadratic, extended four-quarter shock	0.429	0.580	0.147

6.4 Within-regime controls and dispositions

Under the common-window design, the actual residuals are 0.251, 0.438, and 0.372. Their strict ranks are 93.9, 100.0, and 97.0 per cent; 100.0 means that the actual boundary exceeds all 33 controls and is not a zero p -value. Figure 7 shows the control distribution. These percentiles are empirical calibration devices, not universal probabilities. Their purpose is to indicate how unusual a boundary is under the same local design.

For illustration, the registry sets $T_L = 0.12$, $T_H = 0.18$, $P_L = 90$, and $P_H = 97.5$. The historical-window residual places pre--shock in conditional pooling, shock--transition in separation, and transition--post in review. The control percentile upgrades pre--shock to review. Shock--transition remains separate because both its residual and its control rank cross the upper criteria. Transition--post remains under review: its percentile is high but does not strictly exceed 97.5. Table 6 records the evidence without collapsing the translation, residual, percentile, and provenance into a single score.

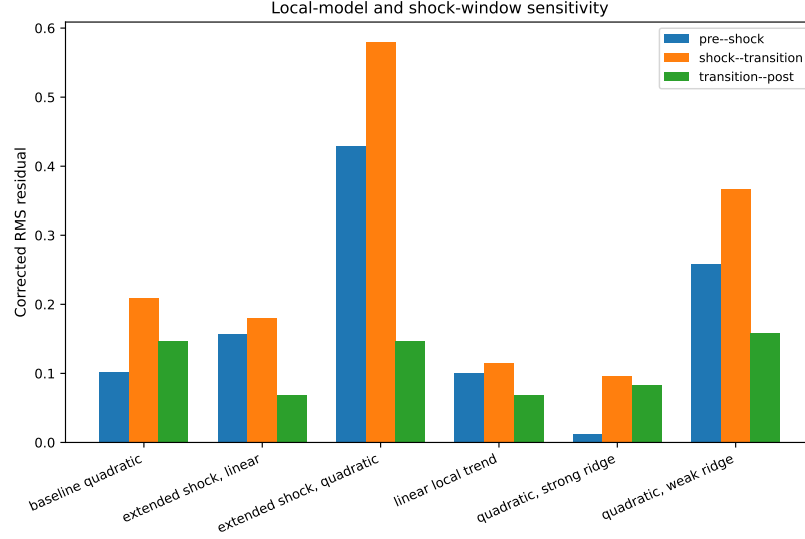


Fig. 5 Sensitivity of historical-window residuals to local polynomial degree, ridge penalty, and shock-window length

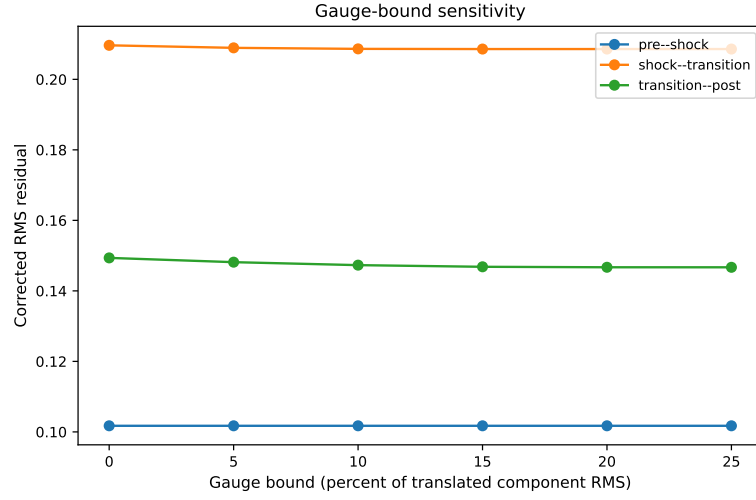


Fig. 6 Sensitivity of historical-window residuals to the authorised correction fraction

The decision table does not validate the illustrative thresholds. A production authority should derive them from the loss attached to false pooling and false separation. The simulation already shows that the same threshold can be conservative at one noise level and permissive at another.

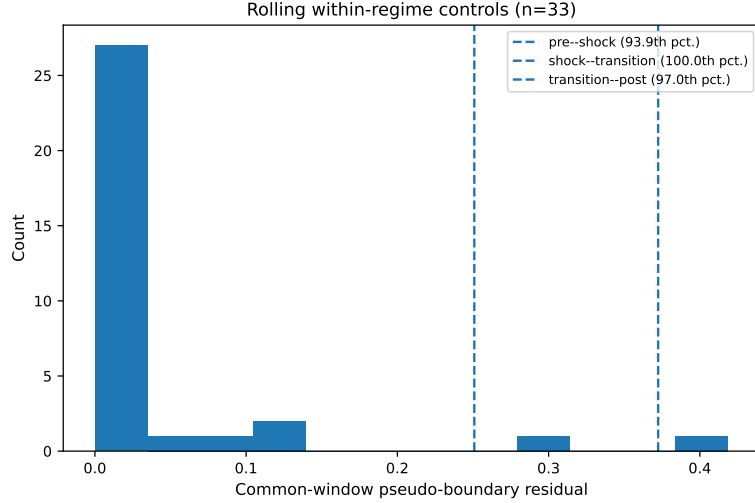


Fig. 7 Common-window actual boundaries and 33 within-regime pseudo-boundary controls

Table 6 Illustrative evidence-integrated dispositions

Boundary	Numerical evidence	Disposition	Required action
pre-shock	$D = 0.102$; common-window rank 93.9%; translation norm 0.518	Review before pooling	Verify source definitions, mapping rules, translation magnitude, and model sensitivity
shock-transition	$D = 0.209$; rank 100.0%; translation norm 0.497	Keep separate	Preserve the regime break unless substantive reconciliation and full-record sign-off are obtained
transition-post	$D = 0.147$; rank 97.0%; translation norm 0.332	Review before pooling	Examine the visible-response component, provenance, and threshold sensitivity

6.5 Threshold sensitivity

The residual-only classification was recomputed on all 16 registered pairs $T_L \in \{0.08, 0.10, 0.12, 0.14\}$ and $T_H \in \{0.16, 0.18, 0.20, 0.22\}$ with $T_H > T_L$. Pre-shock is conditionally poolable in eight pairs and under review in eight; shock-transition is separate in twelve pairs and under review in four; transition-post is under review in all sixteen. Once the registered control-percentile criteria $P_L = 90$ and $P_H = 97.5$ are included, the evidence-integrated sequence is review-separate-review throughout

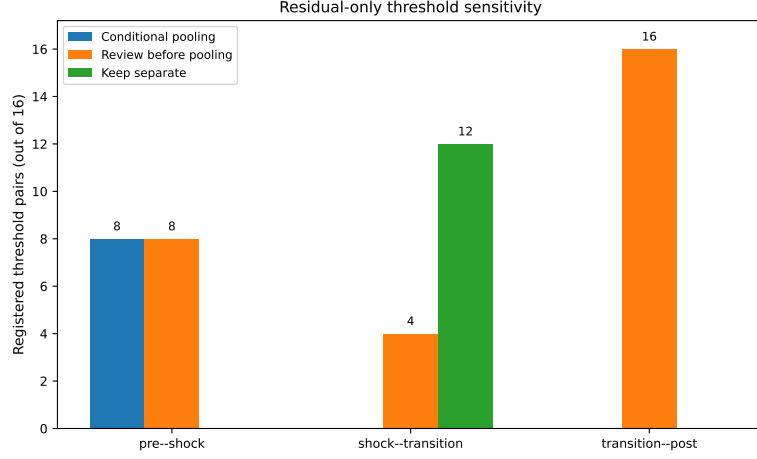


Fig. 8 Residual-only disposition counts across 16 registered threshold pairs. The percentile evidence is excluded from the bars and discussed in the text

this threshold grid. Figure 8 reports the residual-only counts. This exercise does not calibrate the tolerances; it shows which conclusions are threshold-dependent and which are supported independently by the control ranks.

7 Operational protocol for accountable integration

7.1 From mathematical object to administrative record

Each mathematical object has an institutional counterpart. A vertex is a versioned data environment whose record identifies the provider release, variable dictionary, population, native frequency, legal purpose, and responsible office. An edge is an authorised comparison with a declared window, translation, and correction set.

The translation is the level crosswalk proposed for pooling; its norm remains material when the final residual is small. The correction set records tolerable coding or normalisation differences. The residual is what those authorised operations do not remove. The cycle component tests the coherence of the crosswalk network, and the full-record lift tests whether the reconciled values can exist under the applicable rules. Thus a documented unit conversion need not be incompatible, while a small residual need not be admissible.

7.2 Minimum memorandum

A production audit should follow Algorithm 1, begin its memorandum with the proposed disposition, and then provide the evidence by which that disposition can be reproduced or contested. At minimum, the memorandum should contain:

- (M1) the regime environments, boundary dates, and audit windows;
- (M2) source versions, native observation dates, and provider-to-period mapping rules;

- (M3) the audited-variable dictionary and the parts of the full record excluded from numerical comparison;
- (M4) the componentwise translation, its norm, rationale, and any translation-magnitude rule;
- (M5) the authorised correction set and the officer or standard by which it was approved;
- (M6) the residual and its component decomposition;
- (M7) model, deletion, correction, threshold, and pseudo-boundary sensitivities;
- (M8) the graph cycle test where the record network contains loops;
- (M9) the full-record feasibility result or dual certificate;
- (M10) the final action, decision margin, responsible officer, date, and version hash.

A file that records only the final category is not an audit trail.

7.3 How the protocol changes practice

In an indicator warehouse, provider and regime metadata remain attached to the series. In a ministry migration, old and new coding manuals form separate vertices, and the crosswalk is tested before legacy records are rewritten. A keep-separate decision does not prohibit analysis; it requires the break to be modelled. In a multi-agency exchange, the cycle test detects crosswalks for which the reported value depends on the route of conversion.

Responsibility is also divided. The analyst computes the residual but cannot waive a confidentiality rule. The steward may approve a mapping rule but cannot alter the residual. The decision authority signs the disposition and states the loss or quality rationale for the thresholds.

8 Discussion

8.1 Methodological contribution

The method separates claims that are often conflated. Measurement invariance, structural change, provenance, and legal admissibility are not equivalent. A series may fail invariance yet possess a documented crosswalk; it may appear numerically stable yet violate a population rule; pairwise conversions may be acceptable but inconsistent around a cycle. Each case requires a different diagnostic.

Pairwise residuals concern observed overlap windows. The cycle component concerns the conversion registry as a whole. The Tunisian chronology is a chain and therefore has no non-trivial cycle test; cycle and lift failures are demonstrated by explicit examples, not reported as Tunisian estimates. In a multi-source system, the cycle result and the full-record feasibility test should be reported together. The latter turns administrative impossibility into a finite feasibility problem and, where available, a dual certificate.

8.2 What the Tunisian evidence adds

The Tunisian evidence is methodological rather than causal. Level statistics make the pre-shock and transition-post boundaries especially prominent; the post-registration

residual makes shock-transition the most exceptional. The diagnostics therefore distinguish level conversion from residual disagreement in shape.

The shock chart contains two quarters, the absolute residual depends on regularisation, and the provider-to-quarter construction cannot yet be rebuilt from every native release. The evidence supports preserving an explicit shock-transition break in the deposited panel. It neither validates every upstream transformation nor estimates a policy effect.

8.3 Relation to alternative methods

Item-level data with a common latent structure call for measurement-invariance analysis. An unknown break date calls for change-point methods; a deployed predictive stream may call for concept-drift analysis. The present audit applies when boundaries are institutionally defined, records are heterogeneous, a finite crosswalk is proposed, and pooling requires a documented decision.

These methods may enter the audit as edge evidence or replace the local polynomial fit. They do not remove the distinction between edge registration, graph consistency, and full-record feasibility.

8.4 Limitations and research agenda

External validation of the source-aligned panel requires the provider releases, licences, native observation dates, and a completed, executable mapping ledger. The present panel is low-dimensional and author-constructed; administrative systems with full records, coding manuals, and legal constraints would permit direct study of false pooling and false separation.

The thresholds are illustrative. A production rule should minimise an explicit loss or satisfy a regulatory quality standard (Keeney and Raiffa 1976; Morgan and Henrion 1990). The margin theorem analyses stability once thresholds are given; it does not determine them. The windows are also short. Block resampling is used only as a sensitivity calculation, and the stationary-ergodic consistency result in Online Resource 1 does not justify inference from these fixed windows.

The correction set is also constant over each edge window. Time-varying or state-dependent corrections are possible under convexity, but excessive flexibility would remove the disagreement that the audit is intended to measure.

9 Conclusion

Longitudinal integration across institutional change requires several distinct claims: a stated level conversion, a measure of residual shape disagreement, a coherent conversion network, an admissible full-record lift, and a registered disposition.

The graph-based audit gives each claim a separate mathematical and administrative form. In the Tunisian panel, large level changes occur at several boundaries, but shock-transition is the most exceptional after registration and under same-design controls. That break should therefore remain explicit; the adjoining boundaries require review. Computational continuity alone is not evidence of institutional comparability.

Supplementary information

Online Resource 1 contains complete proofs, positive and failure examples, the stationary-ergodic consistency extension, and simulation details. Online Resource 2 contains the anonymised data, registered parameters, executable workflow, generated outputs, and verification records.

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Supplementary Files

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- [ESM2AnonymisedReproducibility.zip](#)