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Multi-Stage Sensitivity Analysis of Single Coin Finds: Challenging Central-Place Models in the Early and High Medieval Rhine-Meuse Delta

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Abstract

Traditional historical perspectives on early medieval urban developments regularly presuppose that elite administrative frameworks, including Carolingian and Ottonian palatia, automatically operated as primary catalysts for centralized, palace-driven trade network growth. However, investigating such top-down assumptions is heavily constrained by highly fragmented written records. This study implements an alternative mathematical framework by conducting a three-stage sensitivity evaluation of an expanding stray-coin dataset (N_A = 25, N_B = 97, and N_C = 116) distributed across four neighboring riverine zones: Neder-Betuwe, Overbetuwe, Tiel, and Nijmegen. Through the concurrent application of Pearson's independence tests, cell-specific adjusted residuals, and sequential alpha corrections, we track the shifting structural relationship between chronological coin cohorts (450 - 1200 CE) and modern municipal boundaries. The statistical results demonstrate that while the broader delta landscape achieved macroeconomic uniformity from the Carolingian horizon onward, Nijmegen followed a highly idiosyncratic institutional trajectory during the post-Roman transition (450 - 600 CE). A significant, localized overrepresentation of early monetary losses consistently resisted all sample expansions. This robust data signature implies that, notwithstanding the proven absence of stable domestic settlement structures within the former Roman center, the site maintained a highly specialized, episodic, or institutional function. Conversely, the post-600 CE regional uniformity directly challenges the palace-centric market model, indicating that high-medieval monetization was propelled by regional ecclesiastical lords surfing upon collective riverine transport corridor dynamics.

Keywords

Multi-Stage Sensitivity Analysis, Numismatics, Post-Roman Transition,

Rhine-Meuse Delta, Spatial Archaeology, Structural Contingency Testing

1. Introduction

Nijmegen occupies a paramount position in the early medieval historiography of the Low Countries. Its development is traditionally linked to the selection of the Valkhof hill as the site for an imperial Carolingian palatium under Charlemagne and successive Ottonian rulers, a topography that profoundly shaped the long-term spatial layout of the settlement (Gorissen, 1956; Hundertmark, 2019; Kloosterman, 2024; Weve, 1993). Standard, top-down historical narratives frequently assume that this elite administrative infrastructure automatically catalyzed a dominant, palace-driven central market economy (Gorissen, 1956; Hodges, 1982). However, verifying these assertions using written records is heavily constrained by the uneven and fragmentary nature of contemporary texts (Bloemers & Thijssen, 1990; Bloemers, 2016; Hendriks et al., 2014; Hendriks & den Braven, 2015; Theuws & den Braven, 2025; Van Enckevort et al., 2017; Van Enckevort, 2021).

In recent decades, the systematic mobilization of single-coin finds has provided an empirical proxy for day-to-day monetary transactions. Unlike deliberate coin hoards, which reflect wealth preservation or acute crisis behaviors, casual loose coin losses offer a reliable measurement of regional monetary circulation intensity and changing institutional boundaries.

When subjected to quantitative testing, Nijmegen's numismatic record presents striking patterns that contextualize developments across the wider landscape. Archaeological evaluations of the post-Roman window (450 - 600 CE) have long demonstrated a severe disruption or absence of stable urban habitation and settlement structures within the old Roman core, a structural hiatus that heavily complicates traditional views on continuity (Bloemers & Thijssen, 1990; Hendriks & den Braven, 2015; Van Enckevort et al., 2017). Crucially, while the urban center reflects this residential gap, peripheral micro-regional networks reveal localized economic resilience and active fluvial exchange outside the abandoned urban core (Hendriks et al., 2014). This complex regional dynamic forces a reassessment of the institutional framework during these transitional centuries (Hendriks & den Braven, 2015).

Furthermore, the subsequent Carolingian and Ottonian horizons show no clear quantitative circulation peak, forcing us to rethink the precise economic impact of the imperial presence on the hill (Den Braven, 2014, 2021; Hendriks et al., 2014; Theuws & den Braven, 2025). This prolonged absence of a monetary surge directly undermines the hypothesis that the imperial palace functioned as a centralized redistributive core. Instead, the most pronounced monetary transformation occurred well before the mid-12th-century imperial interventions of Emperor Frederick Barbarossa, meaning the high-medieval shift was driven by other regional

dynamics (Hundertmark, 2019; Weve, 1993). Between 1100 and 1150 CE, a massive cluster of episcopal coinage appears, tied directly to the Prince-Bishopric of Utrecht. This development suggests that ecclesiastical lords spearheaded the high-medieval economic integration of Nijmegen (Mekking, 1996).

To evaluate the structural resilience of these patterns, this study deploys a rigorous three-stage sensitivity analysis based on an expanding numismatic corpus. By tracking how a controlled dataset expansion from an isolated sample ($N = 25$) to an intermediate baseline ($N = 97$), and ultimately to a comprehensive updated assembly ($N = 116$) affects regional contingency structures, we demonstrate the mathematical robustness of Nijmegen's decentralized trajectory (De Nederlandsche Bank, n.d.; Duchateau, 2026).

2. Materials and Methods

The quantitative architecture of this paper relies on the comparative analysis of single-coin find profiles across four municipalities: Neder-Betuwe, Overbetuwe, Tiel, and Nijmegen (De Nederlandsche Bank, n.d.; Duchateau, 2026). To clarify the distinction between localized sample growth and overall matrix size, the total contingency table counts ($N = 285$, 357, and 376) represent the cumulative aggregation of three regional baselines extracted from the official NUMIS repository—Neder-Betuwe ($N = 61$), Overbetuwe ($N = 106$), and Tiel ($N = 93$)—combined with the sequentially expanding, custom-compiled Numismagus dataset for Nijmegen. This Nijmegen sample expands from the NUMIS core ($N_A = 25$) to Model B ($N_B = 97$). A limitation here is the inclusion of unpublished, preliminary data from recent excavations. Although their exact site contexts remain unresolved, these records are systematically classified as single coins in accordance with standard repository criteria. The dataset reaches its current maximum extension in Model C ($N_C = 116$) by incorporating further specialized excavation reports. This threshold represents a fluid baseline rather than a static total, as both the official NUMIS repository and regional excavation reports are subject to continuous database updates from ongoing field research. Deposition zones were operationalized strictly based on the modern municipal boundaries. Single coins lacking precise registration within these municipal boundaries were excluded from the spatial matrix. To ensure analytical uniformity, the dataset was strictly restricted to individual monetary items. This screening process was operationalized by filtering the source repositories according to predefined database fields: individual finds under "Hoofdindeling" (→ "munten"), accidental losses under "Karakter vondst" (→ "losse vondst"), chronological margins under "Periode" (spanning 450 to 1200 CE), and geographical distribution under "Vindplaats (gemeente)". The resulting sample comprises both isolated surface discoveries and objects recorded during controlled field evaluations. Conversely, para-numismatic artifacts (such as coin brooches) and clustered wealth deposits (hoards) were systematically barred from entry. To establish a clear diachronic framework, the coins are classified into five consecutive 150-year chronological cohorts: 450 - 600 CE (Early post-Roman

transition), 600 - 750 CE (Anglo-Frisian Sceat horizon), 750 - 900 CE (Carolingian Denarius phase), 900 - 1050 CE (Ottonian/Early Holy Roman Empire era), and 1050 - 1200 CE (High Medieval transformation).

To evaluate the structural resilience of the patterns against sequential data expansion, a sensitivity analysis was performed by executing successive chi-square tests of independence across nested contingency frameworks (Models A, B, and C). This approach tracks the behavior of the regional matrix across three evolutionary iterations of the Nijmegen dataset: Model A (The Isolated NUMIS Core, $N = 25$): A controlled sub-sample representing early old-core single finds (De Nederlandsche Bank, n.d.), Model B (The Initial Assembly, $N = 97$): The baseline municipal corpus incorporating the seven preliminarily reported 2025 Winkelsteeg cemetery discoveries (Duchateau, 2026; N001-N097), and Model C (The Expanded Assembly, $N = 116$): The comprehensive updated corpus incorporating an additional 19 single coins gathered via excavation reports (Duchateau, 2026; N001-N116).

Cell-specific adjusted standardized residuals (ASR) were computed across all 20 cells for each model to isolate localized variations. Sequential Holm-Bonferroni corrections ($\alpha = 0.05$) were systematically applied to control for cumulative type-I errors per matrix. The absolute strength of micro-regional differentiation was measured via Cramer's V effect size. Structuring, text-data integration, and analytical validation of the statistical results were assisted by Gemini (Google, Gemini series). All results were critically reviewed and verified by the author.

3. Results

The multi-stage sensitivity analysis demonstrates that the broader micro-regional relationship between chronological periods and deposition zones is statistically significant across all three dataset iterations (**Figure 1**; **Table 1**, **Table 2**). All statistical computations, including Pearson's chi-square tests of independence and cell-specific adjusted standardized residuals (ASR), were executed using Python (version 3.10) via the scipy.stats library framework. Regarding test assumptions, exactly 20.0% of the contingency cells across all three frameworks (4 out of 20 cells per model, confined to the early 450 - 600 CE cohort) yielded an expected frequency below 5, with minimum expected values of 0.53 in Model A, 1.88 in Model B, and 1.78 in Model C. Because these layouts comply precisely with Cochran's standard threshold where no more than 20% of cells contain expected frequencies below 5, the conventional chi-square framework and subsequent ASR evaluations remain mathematically robust against small-sample distortions.

When evaluating Model A utilizing the isolated core database of 25 coins, the overall matrix exhibits a highly significant distribution represented by a chi-square value of χ^2 (12, $N = 285$) = 46.50, where $p < 0.001$ and the effect size stands at $V = 0.23$. Upon moving to Model B with the initial assembly of 97 coins, the regional matrix remains significant, yielding a chi-square value of χ^2 (12, $N = 357$) = 35.84, where $p < 0.001$ and the effect size is $V = 0.18$. Finally, under Model C

incorporating the fully expanded assembly of 116 single coins, the multi-site comparison maintains its statistical significance, showing a chi-square value of χ^2 (12, $N = 376$) = 34.47, where $p < 0.001$ and the overarching regional effect size is calculated at $V = 0.17$.

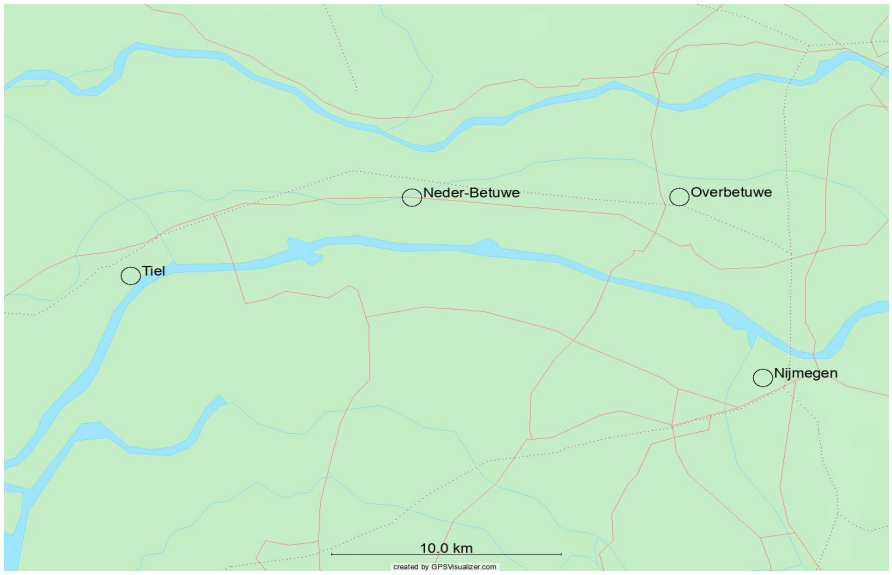

Figure 1. Geographic matrix of the study area within the Rhine-Meuse delta, delineating the four municipal operational cells and fluvial corridors. Map data visualized via GPS Visualizer (n.d.) (https://gpsvisualizer.com, accessed on 25 June 2026).

Table 1. Chronological distribution and frequencies of single coin finds across municipalities and sensitivity models.

Municipality	Chronological Cohorts					
	N	450 - 600	600 - 750	750 - 900	900 - 1050	1050 - 1200
Neder-Betuwe	61	0 (0.0%)	19 (31.1%)	5 (8.2%)	19 (31.1%)	18 (29.5%)
Overbetuwe	106	1 (0.9%)	25 (23.6%)	32 (30.2%)	19 (17.9%)	29 (27.4%)
Tiel	93	1 (1.1%)	22 (23.7%)	15 (16.1%)	18 (19.4%)	37 (39.8%)
Nijmegen (A)	25	4 (16.0%)	7 (28.0%)	7 (28.0%)	3 (12.0%)	4 (16.0%)
Nijmegen (B)	97	9 (9.3%)	19 (19.6%)	22 (22.7%)	18 (18.6%)	29 (29.9%)
Nijmegen (C)	116	9 (7.8%)	19 (16.4%)	25 (21.6%)	22 (19.0%)	41 (35.3%)

Table 2. Summary of Pearson's chi-square test results and effect sizes for sensitivity models A, B, and C.

Model	Model Parameters					
	N	χ^2	*df*	Total *N*	*p*	*V*
Model A	25	46.50	12	285	<0.001	0.23
Model B	97	35.84	12	357	<0.001	0.18
Model C	116	34.47	12	376	<0.001	0.17

Analyzing the cell-specific adjusted standardized residuals under strict sequential Holm-Bonferroni corrections confirms that a single localized anomaly achieves formal statistical significance across all three tested frameworks. In Model A (N = 25), the isolated Nijmegen core displays a robust overrepresentation of early currency losses during the post-Roman transition (450 - 600 CE), yielding an adjusted standardized residual of (ASR = 5.07; $p < 0.001$) (Table 3).

Table 3. Cell-Specific adjusted standardized residuals (ASR) for Model A (isolated core, N = 25).

Municipality	Chronological Cohorts					
	N	450 - 600	600 - 750	750 - 900	900 - 1050	1050 - 1200
Neder-Betuwe	61	−1.29	1.12	−2.72	2.27	−0.26
Overbetuwe	106	−1.05	−0.60	3.04	−0.89	−0.99
Tiel	93	−0.84	−0.53	−1.33	−0.39	2.27
Nijmegen (A)	25	5.07[a]	0.29	0.94	−1.12	−1.69

[a]. $p < 0.05$ after Holm-Bonferroni correction per cell.

Following the dataset expansions in Model B and Model C, this localized anomaly flattens slightly but remains highly resilient rather than dissolving. In Model B (N = 97), the cell persists with an (ASR = 4.14 and $p < 0.001$), and in the fully expanded Model C (N = 116), it firmly survives the strict multi-comparison threshold with an (ASR = 3.72 and $p = 0.004$). The statistical survival of this single cell across all expansions proves that Nijmegen's early post-Roman numismatic signature is a genuine structural feature of the archaeological record, whereas all subsequent periods show a mathematically balanced and homogeneous regional distribution (Table 4, Table 5). To verify the underlying mathematical validity of these comparisons, the complete matrix of expected cell frequencies is provided in Table 6.

4. Discussion

The most profound revelation of the multi-stage sensitivity analysis is the resilience of a distinct spatial and economic boundary separating Nijmegen from its

Table 4. Cell-specific adjusted standardized residuals (ASR) for Model B (initial assembly, N = 97).

Municipality	Chronological Cohorts					
	N	450 - 600	600 - 750	750 - 900	900 - 1050	1050 - 1200
Neder-Betuwe	61	−1.53	1.48	−2.65	2.21	−0.40
Overbetuwe	106	−1.52	−0.07	2.87	−0.85	−1.13
Tiel	93	−1.30	−0.04	−1.27	−0.38	1.96
Nijmegen (B)	97	4.14[a]	−1.14	0.56	−0.62	−0.44

[a]. $p < 0.05$ after Holm-Bonferroni correction per cell.

Table 5. Cell-Specific adjusted standardized residuals (ASR) for Model C (expanded assembly, $N = 116$).

Municipality	Chronological Cohorts					
	N	450 - 600	600 - 750	750 - 900	900 - 1050	1050 - 1200
Neder-Betuwe	61	−1.48	1.74	−2.60	2.19	−0.68
Overbetuwe	106	−1.43	0.28	2.93	−0.85	−1.52
Tiel	93	−1.22	0.28	−1.20	−0.38	1.54
Nijmegen (C)	116	3.72[a]	−1.93	0.34	−0.57	0.58

[a]. $p < 0.05$ after Holm-Bonferroni correction per cell.

Table 6. Expected cell frequencies across sensitivity models A, B, and C.

Municipality	Chronological Cohorts					
	Model	450 - 600	600 - 750	750 - 900	900 - 1050	1050 - 1200
Neder-Betuwe ($N = 61$)	A	1.28	15.62	12.63	12.63	18.84
	B	1.88	14.52	12.64	12.64	19.31
	C	1.78	13.79	12.49	12.65	20.28
Overbetuwe ($N = 106$)	A	2.23	27.15	21.94	21.94	32.73
	B	3.27	25.24	21.97	21.97	33.55
	C	3.10	23.96	21.71	21.99	35.24
Tiel ($N = 93$)	A	1.96	23.82	19.25	19.25	28.72
	B	2.87	22.14	19.28	19.28	29.44
	C	2.72	21.02	19.05	19.29	30.92
Nijmegen (A: 25 |B: 97| C: 116)	A	0.53	6.40	5.18	5.18	7.72
	B	2.99	23.10	20.11	20.11	30.70
	C	3.39	26.22	23.76	24.06	38.56

micro-regional hinterland exclusively during the post-Roman transition (450 - 600 CE). The fact that the 450 - 600 CE Nijmegen cell resists the stringent mathematical penalties of sequential Holm-Bonferroni corrections across all three database expansions—maintaining statistical significance from Model A through the fully expanded Model C—proves that the old Roman core possessed a structurally unique economic or depositional profile.

This statistical divergence challenges traditional localized assumptions. Archaeological evaluations of the post-Roman window (450 - 600 CE) have long demonstrated a severe disruption or absence of stable urban habitation and settlement structures within the old Roman core. This structural discontinuity is well-documented in regional syntheses (Bloemers & Thijssen, 1990; Van Enckevort et al., 2017). Crucially, while the urban center reflects this residential gap, peripheral micro-regional networks—particularly documented across the rural clusters of the Neder-Betuwe and adjacent landforms—reveal localized economic resilience

and active fluvial exchange outside the abandoned urban core (Bloemers, 2016; Hendriks et al., 2014). The persistent overrepresentation of single coin losses in Nijmegen during this exact phase (ASR = 3.72 in Model C) indicates that despite the residential abandonment of the Roman center, the location retained a highly specialized, episodic, or institutional function that drew a disproportionate concentration of early currency compared to the surrounding Neder-Betuwe, Overbetuwe, and Tiel. This underscores that the site's role was far more complex than simple domestic occupation would suggest (Hendriks & den Braven, 2015).

However, a dramatic structural shift occurs immediately after the 600 CE horizon. During the subsequent Carolingian, Ottonian, and High Medieval eras, the total absence of localized cell anomalies demonstrates that the data from the central river area show an absence of statistically significant spatial boundaries between the riverine zones post-600 CE. Once sample sizes grow to representative levels in Model B and Model C, the statistical boundaries between the Neder-Betuwe, Overbetuwe, Tiel, and Nijmegen effectively evaporate for all periods following the post-Roman transition. This means that while the cross-river delta did not operate as a single economic organism from the outset, it rapidly coalesced from the 7th century onward.

This lack of strong regional differentiation after 600 CE challenges top-down historiographical paradigms that treat major institutional sites as isolated economic monoliths. Traditional historical narratives have treated the imperial presence at the Carolingian palatium of Nijmegen or the royal trading town status of Tiel as exceptional localized market drivers (Gorissen, 1956; Oudhof et al., 2013). Had these administrative centers generated distinct, self-contained commercial market dynamics, they would exhibit sharp, statistically significant positive residuals during their respective operational peaks.

Instead, the flatline of the Carolingian and Ottonian horizons across all sectors demonstrates that these administrative installations did not alter the broader economic friction of the delta landscape. The subsequent Carolingian and Ottonian horizons show no clear quantitative circulation peak. This prolonged absence of a monetary surge directly undermines the hypothesis that the imperial palace functioned as a centralized redistributive core. The Valkhof palace functioned as a critical logistical and symbolic outpost within an itinerant network rather than a centralized redistributive core, a dynamic confirmed by recent refuse and stratigraphical analyses (Van Enckevort, 2021). Even when elite architecture was deployed to project administrative power and validate imperial status, these interventions remained localized (Mekking, 1996, 1997; Verhoeven, 2021). The monetary circulation followed the overarching chronological waves of the entire riverine corridor, meaning that imperial or ecclesiastical interventions did not create localized economic anomalies but rather surfed upon wider, shared delta-wide economic developments.

Furthermore, the subsequent high-medieval monetary transformation occurred well before the mid-12th-century imperial interventions of Emperor Fred-

erick Barbarossa. Between 1100 and 1150 CE, a massive cluster of episcopal coinage appears, tied directly to the Prince-Bishopric of Utrecht (Van der Chijs, 1859). This development suggests that ecclesiastical lords spearheaded the high-medieval economic integration of Nijmegen. This process predates the major structural and architectural expansions later executed at the castle complex (Mekking, 1996, 1997; Perlich & van Tussenbroek, 2008; Weve, 1993). Yet, because this transformation (1050 - 1200 CE) exhibits no statistically significant cell-specific variance across the matrix, it confirms that Utrecht's ecclesiastical monetization strategy was not restricted to Nijmegen, but was uniformly absorbed across the entire micro-region. This regional synchronization is strongly supported by localized excavations in key peripheral nodes, such as the multi-period sanctuary site at Elst, which demonstrates parallel long-term structural and cultural transitions within the surrounding river landscape (Derks et al., 2008).

This shared, deeply interconnected chronological trajectory across the Neder-Betuwe, Overbetuwe, Tiel, and Nijmegen reflects the profound connectivity provided by the natural fluvial networks of the Waal and Rhine. Protected by natural Pleistocene elevations and adaptive land use, these adjacent nodes absorbed environmental disruptions and flood events as a collective whole (Willemse, 2019). The post-600 CE absence of cell-specific statistical variance underscores that the flow of currency became entirely fluid across river boundaries, confirming a highly integrated corridor where local exchange networks operated in unison throughout the Middle Ages, long after outgrowing the unique structural friction of the early post-Roman transition. A clear limitation of this numismatic approach is that absolute find frequencies do not solely mirror monetary circulation; they are concurrently shaped by archaeological recovery traits, depositional behaviors, and variable metal-detection practices across the delta.

5. Conclusion

The multi-stage sensitivity analysis of the Numismagus corpus across three distinct dataset sizes confirms three distinct features of Nijmegen's early medieval trajectory:

Multi-site contingency testing proves that Nijmegen maintained a structurally unique, high-intensity numismatic profile during the post-Roman transition (450 - 600 CE). This phase was characterized by an exceptionally resilient overrepresentation of single coins that survives all dataset expansions. This mathematical finding aligns with physical evidence of structural disruption in the urban core, proving that the location retained a specialized, institutional function despite residential abandonment (Bloemers & Thijssen, 1990; Hendriks & den Braven, 2015; Van Enckevort et al., 2017).

Following this initial period of post-Roman friction, the statistical boundaries between the Neder-Betuwe, Overbetuwe, Tiel, and Nijmegen effectively evaporated. From 600 CE onward, currency flowed fluidly across cross-river nodes without creating localized anomalies, confirming that the delta integrated into a single mac-

roeconomic network over the long term. This fluid monetization process was later reinforced by the uniform micro-regional absorption of Utrecht's episcopal coinage, which predated the subsequent Hohenstaufen fortifications (Hundertmark, 2019; Kloosterman, 2024; Mekking, 1996, 1997; Perlich & van Tussenbroek, 2008; Weve, 1993).

The data confirms that Nijmegen did not host an isolated, palace-driven Carolingian or Ottonian market economy. Its development from the 7th century onward was fully synchronized with the broader, decentralized economic rhythms of the Rhine-Meuse delta, despite its unique post-Roman starting point. This proves that imperial administrative infrastructure on the hill functioned primarily within a symbolic and itinerant framework rather than acting as an isolated economic driver (Gorissen, 1956; Kloosterman, 2024; Van Enckevort, 2021; Verhoeven, 2021).

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Data Availability Statement

The complete source data for this study, compiled as the Numismagus dataset Version 2 (consisting of individual coin records N001-N116), has been deposited for open access on Figshare (https://doi.org/10.6084/m9.figshare.32486373). Public reference data from the NUMIS repository remain directly accessible via De Nederlandsche Bank at https://www.denieuweschatkamer.nl.

Conflicts of Interest

The author confirms that there are no competing financial, institutional, or personal interests that could have influenced the objectivity of this research.

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