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Highlights

- monetary landscape: digital (credit/debit cards) and physical (cash) payments;
- optimal combination between environmentally sustainable and safe payment methods;
- non-cooperative differential game with European payment data;
- baseline symmetric Nash model and Stackelberg extension;
- policy implications for digital financial risks and their security dynamics.

Cash or card – combat or coexistence? A non-cooperative differential game approach.

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Abstract

The present letter analyses the current evolution of the monetary landscape mostly characterized by means of payments based on digitization (e.g., credit/debit cards) to the disadvantage of physical ones (e.g., cash). In parallel, pleas for a more sustainable lifestyle are increasingly heard by the banking and financial sector providing payment solutions, which should be also perceived to be sufficiently secure against frauds. For instance, fraud losses due to identity theft are at a cross-country level on the surge for credit-card payments while cash is considered less practical and connected with operational and logistical challenges (e.g., production and issuance, return, sorting and destruction). In the light of these developments and trade-offs, we derive the optimal combination of (digital versus physical) means of payments to pay in an environmentally sustainable and safe way. By means of a non-cooperative differential game, this letter provides a baseline symmetric Nash model supplemented by a Stackelberg extension capturing realistic leader-follower dynamics and calibrates both frameworks to European payment data. We derive closed-form solutions and discuss coexistence conditions for optimal payment systems and suggest directions for future, empirically more sophisticated extensions.

Keywords: cash-cashless equilibrium; differential games; financial sustainability; monetary policy; Nash equilibrium; payment systems

JEL Codes: C61, C72, E42, E58

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1. Introduction

After more than a millennium since the first "true" banknote in China (i.e., around 960 CE (Guan et al., 2024)) and galloping digitization of payment instruments in the wake of the Digital Revolution (20th Century –), are there still arguments for paying with (heavy) metal coins and (cotton-based) banknotes? A credit/debit card system[1] is convenient in having an (in principle) unbounded financial capacity at hand. However, banknotes and coins work independently of card readers and digital systems (Di Iorio and Rocco, 2025) – not to speak of critical energy sources such as electricity. A stolen credit/debit card can lead to higher losses[2] – for instance, "[i]n 2024, U.S. consumers suffered over $12.5 billion in fraud losses, a 25% increase from 2023" (Clearly Payments, 2024) with 185,166 fraud reports (out of 475,905 for all payment methods) involving credit cards and losses reaching $455 million compared to 13,609 reports and $308 million losses for cash (Federal Trade Commission 2025, p. 11) – but can be disabled quickly while stolen cash is hard to get back at all. Furthermore, unreported thefts could be significant in total, as no action might be taken for small amounts.

While central banks and States guarantee the reliability of the cash supply, a card system is run by private providers (Beretta and Neuberger, 2025). Although providers have to fulfill regulatory requirements, States might provide more stability based on the principle that "[p]rivate money exists in modern financial systems as a complement to public money which is the only form of money having legal tender status" (Martino 2024, p. 4). Cash still is an hedging instrument against negative interest rates (whose usage increases under such circumstances (Liñares-Zegarra and Willesson, 2021)) while a credit/debit card might not be. According to Oxford Economics (2024) the main advantages of digital payments (as seen by users) are that users don't need to carry a load of cash, the payment process is faster and easier, which might in turn fuel "individuals' overall spending" (Meyll and Walter, 2019). The main benefits of cash are the higher awareness of expenses, better protection of privacy and immediate settlement of transactions. But how about costs and other performance measures? For instance, digital payments might present an environmental advantage as cash is first produced, then issued, afterwards returned, sorted and destroyed (Swiss National Bank, 2025), which might disappear if more users intensify digital payments. The available infrastructure is also decisive for the environmental impact (Oxford Economics, 2024) but even the material which the payment instrument is made of, leading to advertisements of "green debit cards" from recycled ocean plastic "contributing to reforestation with every purchase" (Mastercard, 2021).

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[1] For simplicity, this letter considers only credit and debit cards among available digital payment methods because of representing in several countries the most used payment instruments of consumers (e.g., in the United States in 2025, "credit and debit cards accounted for 35% and 30% of payments, respectively" (Bayeh et al., 2025)).

[2] This is even more verified for bank transfers or payments (i.e., another type of digital, book-to-book settlement) which suffered losses for $2.1 billion over 47,336 fraud reports (Federal Trade Commission 2025, p. 11).

The ecological dimension adds another layer of complexity. Although digital payments are often considered more environmentally friendly, thorough life cycle assessment shows that the environmental impact difference between cash and digital payments is smaller than commonly assumed. Additionally, Oxford Economics (2024) noted that both payment systems bear relatively small environmental impacts overall.

Digital payment infrastructures have become an integral component of the financial system and of modern banking intermediation. They influence liquidity management, transaction costs, and the transmission of monetary policy, thereby contributing to the stability of financial markets. Understanding the dynamics of coexistence and substitution between cash and digital instruments is not only an economic question, but provides insights into how the financial system absorbs technological change while preserving market efficiency and systemic stability. (Adrian and Mancini-Griffoli, 2021; Niepelt, 2022). This letter contributes to the analysis of digital financial risks and their security dynamics in complex ecosystems, which ranges from the impact of digital financial literacy (DFI) on fragile borrowing patterns (Xie, 2025) often triggered by the "neural impact of novel payment instruments in stimulating spending" (Banker et al., 2021) to the relevance of multi-source signals to predict risk events like cryptocurrency pin-bar reversals (Ke et al., 2025) and complements studies on the risk trade-off between mobile payments due to cybercrime, theft and losses and cash due to infectious disease transmission (Pal et al., 2025).

2. Model framework

We integrate the existing literature, which mostly analyzes the impact of means of payments separately (e.g., digital payments only) and regarding a single aspect (e.g., digital payments sustainable economic growth like in Kahveci and Gurgur (2025)).

Our model incorporates instead considerations on safety *and* sustainability, treating cash and cashless payment methods as competing entities in a non-cooperative game. We derive closed-form solutions for the Nash equilibrium, offering insights into the conditions under which different payment methods optimally coexist. Moreover, we provide an overview of potential future model extensions.

2.1. Game structure and players

We model the payment system of a nation as a non-cooperative differential game between two players representing different payment methods:

- **player 1:** cash, controlling usage rate $u_1(t)$;
- **player 2:** cashless, controlling usage rate $u_2(t)$.

The control variables $u_i(t)$, $i = 1,2$, represent total transactions by instrument i at time t. Each player independently selects a usage rate maximizing its objective function assuming the opponent's strategy as given. This results in a Nash equilibrium. Table 1 provides insights into the evolution of cash ($u_1(t)$) and credit/debit card ($u_2(t)$) use over time in selected countries.

[INSERT TABLE 1 HERE]

2.2. State dynamics

We define a state variable $G(t)$ representing the aggregate reputation or utility of the payment system, encompassing safety and sustainability dimensions:

$$\dot{G}(t) = k_1 u_1(t) + k_2 u_2(t) - \delta G(t) \tag{1}$$

[INSERT TABLE 2 HERE]

Here, the parameter k_i measures the net utility differential between safety benefits a_i and environmental costs b_i. Empirically, a_i reflects consumer valuations from multiple perspectives. For instance, the U.S. Federal Trade Commission (2025) documents fraud losses of $455 million for credit cards and $308 million for cash despite 35× higher card usage. Cash exhibits higher perceived safety ($a_1 > a_2$) due to consumer behavior preferences when paying rather than carrying it (Kosse 2013, p. 82, 84) and to its systemic risk mitigation and independence from technological failures (Faella and Zamora-Pérez, 2025). Environmental costs b_i derive instead from lifecycle assessments: digital payments generate 2.1–23.6× lower warming potential than cash ($b_1 > b_2$) through lower initial infrastructure requirements, energy consumption, and carbon emissions, although both systems bear minimal overall environmental impacts (Oxford Economics 2024, p. 161). The decay rate $\delta > 0$ reflects the depreciation of the reputation of the payment methods by ageing infrastructure and security challenges.

[INSERT TABLE 3 HERE]

Table 3 maps the contribution to global warming (GWC) of each payment method and explains why we can, on average, assume for $b_1 > b_2$.

2.3. Objective functions

Each payment instrument aims to maximize its discounted net benefit over its lifetime usually modelled by an infinite horizon:

$$J_i = \int_0^{+\infty} e^{-\rho t} \left[p_i G(t) - \frac{1}{2} c_i u_i(t)^2 \right] dt \tag{2}$$

The objective function consists of two components:

- **benefit**: $p_i G(t)$ represents the instrument's ability to extract value from the system's reputation, where $p_i > 0$ measures market share sensitivity to system reputation;
- **cost:** $\frac{1}{2} c_i u_i(t)^2$ captures quadratic operational costs, where $c_i > 0$ represents the cost parameter for maintaining usage rate $u_i(t)$.

The discount rate $\rho > 0$ reflects standard time preferences in dynamic optimization.

3. Nash equilibrium solution

3.1. Hamilton-Jacobi-Bellman equations

For the non-cooperative differential game, the player's value function $V_i(G,t)$ satisfies the Hamilton-Jacobi-Bellman (HJB) equations, which in our setting are

$$\rho V_i = \max_{u_i}\left\{p_i G - \frac{1}{2}c_i u_i^2 + \frac{\partial V_i}{\partial G}[k_1 u_1 + k_2 u_2 - \delta G]\right\} \tag{3}$$

3.2. Optimal strategies

Maximizing the right-hand side of Eq. (3) with respect to u_i leads to the first-order conditions:

$$u_1^* = \frac{k_1}{c_1}V_1'(G), \quad u_2^* = \frac{k_2}{c_2}V_2'(G). \tag{4}$$

We assume that the optimal feedback strategies are functions of the state variable G, and adopt a linear ansatz for the value functions: $V_i(G) = \alpha_i G + \beta_i$. Substituting this into the HJB equations and matching the coefficients yields:

$$\begin{cases} \alpha_1 = \dfrac{p_1}{\rho + \delta} \\ \alpha_2 = \dfrac{p_2}{\rho + \delta} \\ \beta_1 = \dfrac{p_1}{\rho(\rho + \delta)^2}\left[\dfrac{k_1^2}{2c_1}p_1 + \dfrac{k_2^2}{c_2}p_2\right] \\ \beta_2 = \dfrac{p_2}{\rho(\rho + \delta)^2}\left[\dfrac{k_2^2}{2c_2}p_2 + \dfrac{k_1^2}{c_1}p_1\right] \end{cases} \tag{5}$$

3.3. Equilibrium results

We hence obtain the Nash equilibrium strategies:

$$u_1^* = \frac{k_1 p_1}{(\rho + \delta)c_1}, \qquad u_2^* = \frac{k_2 p_2}{(\rho + \delta)c_2} \tag{6}$$

and the steady-state reputation level converges to:

$$G^* = \frac{1}{\delta(\rho + \delta)}\left[\frac{k_1^2 p_1}{c_1} + \frac{k_2^2 p_2}{c_2}\right] \tag{7}$$

This leads to:

Proposition. *Under the linear-quadratic structure with constant parameters, the unique Nash equilibrium features constant usage rates given by Eq. (6). The equilibrium usage rate for each instrument increases with its safety-sustainability advantage (k_i) and market sensitivity (p_i). It decreases with operational costs (c_i) and the discount-adjusted reputation decay rate ($\rho + \delta$).*

The symmetric configuration provides a theoretical benchmark: both instruments maintain positive usage rates when $k_i > 0$. Hence, optimal payment systems feature coexistence rather than dominance. More precisely, as long as a payment system maintains higher advantages than disadvantages, it will stay in the mix.

4. Extension: Stackelberg leadership dynamics

The symmetric Nash model assumes identical strategic capacities. However, empirical reality suggests asymmetric roles. We extend the framework by introducing a hierarchical structure: cashless (Player 2) acts as leader, anticipating cash's passive response.

4.1. Leader-follower equilibrium

Under the cashless leader's linear feedback control $u_2(G) = \beta + \alpha G$, the cash player's current-value HJB with ansatz $V_1(G) = a_1 + \beta_1 G$ yields the constant best response:

$$u_1^* = \frac{p_1}{c_1} \tag{8}$$

The leader's HJB with quadratic value function $V_2(G) = a_2 + \beta_2 G + \gamma_2 G^2$ yields the algebraic constraint:

$$X^2 - \frac{c_2}{k_2}(2\delta + \rho)(X - p_2) = 0, \quad X := p_2 + 2k_2\gamma_2 \tag{9}$$

The stable branch characterizes the leader's feedback through coefficients:

$$\alpha = \frac{X}{c_2}, \quad \beta = \frac{k_2\beta_2}{c_2} \tag{10}$$

The resulting state dynamics is affine:

$$\dot{G}(t) = (k_1 u_1^* + k_2\beta) - (\delta - k_2\alpha)G(t) \tag{11}$$

with solution:

$$G(t) = G_\infty^S + (G_0 - G_\infty^S)e^{-(\delta - k_2\alpha)t}, \quad G_\infty^S = \frac{k_1 u_1^* + k_2\beta}{\delta - k_2\alpha} \tag{12}$$

The Stackelberg equilibrium implies a higher asymptotic reputation level G_∞^S compared to the symmetric benchmark $G_\infty^N = (k_1 u_1^* + k_2\beta)/\delta$. This results from the reduction of the effective decay term $(\delta - k_2\alpha)$ and, potentially, from a larger numerator reflecting stronger investment incentives. Maintaining a positive and stable reputation level requires a sufficiently high discount rate – typically higher than in the symmetric setting – to prevent divergence of $G(t)$.

Although the cashless provider acting as the Stackelberg leader is consistent with current market structures, leadership in payment ecosystems may shift in case of policy interventions (e.g., through central bank digital currencies (CBDCs) or binding regulatory requirements on payment acceptance).

This scenario can be accommodated without introducing a new control variable, by allowing policy actions to affect the parameters of the leader's feedback rule rather than the strategic structure of the game. Specifically, a policy intensity $m \geq 0$ (capturing CBDC adoption, subsidies, or acceptance mandates) can be modeled as a shift in the intercept of the cashless feedback rule, $u_2(G) = \beta + \alpha G + \theta m$, with $\theta > 0$, where m is exogenous to the providers' strategic decisions.

The resulting closed-loop reputation dynamics remain affine:

$$\dot{G}(t) = (k_1 u_1 + k_2\beta + k_2\theta m) - (\delta - k_2\alpha)G(t) \tag{13}$$

and the steady-state reputation level becomes:

$$G_\infty^S(m) = \frac{k_1 u_1 + k_2\beta + k_2\theta m}{\delta - k_2\alpha} \tag{14}$$

Hence, policy-induced leadership affects both transition dynamics and the steady-state level of adoption while preserving tractability and stability conditions. In contrast to private leaders, regulators can choose the policy intensity m by balancing efficiency, financial inclusion, and system resilience. From this perspective, CBDC-related interventions may endogenously reallocate leadership within the payment system and, if sufficiently strong, shift the steady state from coexistence toward more pronounced substitution dynamics. The structure of payment systems may therefore depend both on private innovation and design of public instruments capable of reassigning leadership and reshaping transition risks.

A regime-switching extension based on a trust threshold, distinguishing Stackelberg and Nash dynamics, is summarized in Table 5.

4.2. Calibration to European payment data

To ensure consistency with observed market conditions, we adopt a minimal calibration strategy. Set $k_1 = k_2 = 1$, $u_1 = 0.4$, and choose convergence speed such that the system reaches 95% of steady state within $L = 6$ years[†]:

$$\lambda := \delta - k_2\alpha = \frac{1}{L}\ln(20) \approx 0.4993\,, \quad \delta = 1 \Rightarrow \alpha \approx 0.5007 \tag{15}$$

For a target long-run cashless share $s \in [0,1]$, the intercept parameter follows from $u_2^\infty = s$:

$$\beta = \frac{s - \alpha k_1 \lambda^{-1} u_1}{1 + \alpha k_2 \lambda^{-1}} \tag{16}$$

The closed-form expression in Eq. (16) follows from substituting Eq. (12) for G_∞^S into the feedback rule $u_2(G) = \beta + \alpha G = s$. Solving for the intercept term βensures that the long-run share of cashless usage u_2^∞ matches the target value s. This calibration preserves the stability constraint $\delta > k_2\alpha$ and links the behavioral parameters α, β to observable country-level adoption rates. Applying this to observed cashless usage shares (Finland: 81%; Germany: 37%; Italy: 31%) yields the results in Table 4.

[INSERT TABLE 4 HERE]

[†] The symmetric parameterization $k_1 = k_2 = 1$ in calibration represents the null hypothesis of balanced net effects. Departures are explored via sensitivity analysis in the Appendix.

Negative β values indicate that reputation-driven dynamics αG dominate constant components in certain markets – a mathematically valid and economically interpretable phenomenon. The model reproduces structurally heterogeneous payment environments using parsimonious parametrization and linking observed cross-country differences to underlying structural determinants.

This calibration confirms that the symmetric model generates stable coexistence equilibria consistent with observed payment environments. Dominance does not emerge endogenously: structural asymmetries or policy shocks are required for displacement to occur.

5. Discussion

5.1. Policy implications

Our theoretical framework, although simplified, provides several policy insights to be later explored with more detailed versions of the present model. Table 5 summarizes the main policy implications.

[INSERT TABLE 5 HERE]

5.2. Research limitations and future perspectives

Assuming identical providers allows for a clear, tractable characterization of equilibrium behavior, clarifying the key trade-offs between adoption speed, adjustment costs, and system stability (Broekhoff and van der Cruijsen, 2024). Although this simplification abstracts from relevant heterogeneities (e.g., differences in strategic capacity, demographic structure, or regulatory exposure), it provides a transparent analytical setting from which complex interactions can be explored in the future.

Within this baseline framework, our model demonstrates how fundamental parameters (e.g., the discount rate, marginal costs, adaptation speed, and decay) shape both coexistence and competition between cash and cashless instruments. These findings provide insights into the resilience and sustainability of competing transaction channels:

- **from a financial perspective:** the coexistence equilibrium identified is interpretable as a condition of liquidity-channel stability. The gradual transition from cash to digital payments affects the velocity of money, transaction costs, and liquidity management practices of banks and market intermediaries (Bordo and Levin, 2019; Chen and Jiang, 2025). The dynamic trajectories generated by the model offer insights into how innovation and regulation jointly shape the resilience of payment infrastructures and the robustness of financial markets;
- **from a managerial perspective:** the analysis illustrates how cost efficiency, technological inertia, and users' temporal preferences influence long-run equilibria and market shares;
- **from a policy perspective:** the symmetric model offers a benchmark for evaluating the effects of policy interventions (e.g., digital incentives, cash-use restrictions (European Consumer Centre France, 2024), or environmental constraints) on market balances, financial inclusion, and stability.

Future developments may introduce structural asymmetries, Stackelberg-type strategic leadership, regime switching, or exogenous shocks affecting stability and welfare. Cross-country comparison and integration with environmental or sustainability frameworks could enhance the model's interpretive power and support assessment of efficiency, inclusion, and social impact in the transition toward less cash-dependent payment ecosystems.

6. Conclusion

The symmetric configuration provides a theoretical benchmark for analyzing dynamic interaction between cash and digital payment instruments, converging toward persistent coexistence rather than dominance. Through financial lens, this equilibrium balances technological efficiency, market incentives, and regulatory sustainability, mitigating concentration risks and promoting financial stability. Dominance arises only from strategic, technological, or institutional asymmetries introduced by the financial sector or State. The hierarchical (Stackelberg) extension reveals that payment-system evolution depends on technological efficiency, adaptive dynamics, and regulatory balance. Empirical calibration validates this interpretation, reproducing observed cross-country patterns with a small, economically interpretable parameter set.

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Declaration of competing interest

None.

Data availability

Data will be made available on request.

Appendix

We now assess robustness to changes in the net-effect parameters $k_i = a_i - b_i$, as defined in Section 2.2. (Table A.1). We consider symmetric variations $k_1 = k_2 \in \{0.6, 0.8, 1.0, 1.2, 1.4\}$ In a predictive exercise, the calibrated parameters α and β are held fixed; in a recalibration exercise, the intercept parameter β is adjusted to match each country's observed long-run cashless share. Symmetric increases in k_2 raise the steady-state reputation level and the implied long-run cashless usage intensity (not constrained to the unit interval). Under recalibration, where $u_2^\infty = s$, long-run shares are preserved by construction and changes in k_i are reflected in the implied intercept and reputation stock. All reported scenarios satisfy the stability condition.

[INSERT TABLE A.1 HERE]

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Table 1

Share of payment instrument (cash versus credit/debit card) use for in-person or point of sale (POS) payments (2019[3], 2024)

	Cash		Credit/ debit card	
	2019	2024	2019	2024
Euro Area	72%	52%	25%	39%
United States	26%	17%	54%	78%

Note: own elaboration of Bayeh et al. (2025, p. 5) and European Central Bank (2020, p. 14).

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[3] Data for 2019 are of particular interest because of pertaining to the year immediately before the Covid-19 pandemic, which boosted the surge of digital means of payment (Bank for International Settlements, 2021).

Table 2

Fraud reports and losses by payment method (2019, 2024)

	Cash		Credit/ debit card	
	2019	2024	2019	2024
Number of reports	12,411	13,609	53,763	185,166
Losses	$120 million	$308 million	$135 million	$455 million

Note: own elaboration of Federal Trade Commission (2025, p. 11; 2020, p. 11).

Table 3

Global warming contribution (GWC) of cash and credit/debit cards depending on their lifecycle phase (kg CO_2 eq.)

	Finland		Germany		Italy	
	Cash	Credit/ debit card	Cash	Credit/ debit card	Cash	Credit/ debit card
Production phase	0.00665	0.00113	0.00554	0.001946743	0.003278243	0.004093658
Operation phase	0.044925097	0.000976	0.0124	0.000919	0.008045577	0.00409
End-of-life phase	0.000219	0.0000876	0.000165	0.000190042	0.000190027	0.000406937

Note: own elaboration of Oxford Economics (2024, p. 242-259).

Table 4

European calibration

Country	Target s	β	G_∞
Finland	0.81	0.204	1.210
Germany	0.37	-0.016	0.770
Italy	0.31	-0.046	0.710

Note: own elaboration.

Table 5

Policy insights of theoretical framework

Policy insights of theoretical frameworkPolicy Domain	Target Institution	Key Findings	Implementation
Coexistence framework	Payment system regulators	Optimal payment systems feature diversity with both instruments maintaining positive usage rates at equilibrium. Complete dominance is suboptimal; coexistence avoids hidden welfare costs (Lastrapes, 2018; McAndrews, 2020)	Preserve dual-instrument ecosystems; avoid policies forcing monopoly dominance
Environmental policy	Environmental/ Financial regulators	Increasing environmental cost differential ($b_1 - b_2$) shifts equilibrium toward the more sustainable instrument but benefits diminish over time due to quadratic cost structure.	Calibrate environmental cost adjustments; monitor diminishing returns in policy effectiveness
Safety regulation	Payment system operators; Central banks	Safety improvements enhance overall system reputation but, depending on relative melioration, do not necessarily favor one instrument over another.	Implement balanced safety improvements across both instruments
Central bank policy	Central banks	Focus on optimizing aggregate system parameters (infrastructure costs) rather than favoring specific instruments. Instrument choice depends on transaction characteristics, merchant acceptance, and infrastructure availability (Di Iorio and Rocco, 2025; Wakamori and Welte, 2017).	Concentrate on infrastructure investment and cost-benefit optimization rather than selective promotion
Hierarchical structure (Stackelberg) - 1	Digital payment leaders (e.g., tech	Digital leadership accelerates cashless adoption but does not eliminate cash usage. Structural	Monitor hierarchical effects; recognize that leadership changes

	firms, card networks)	asymmetries alter adjustment speed, not the coexistence equilibrium itself.	dynamics but not long-term coexistence
Hierarchical structure (Stackelberg) - 2	Policy leadership and CBDC	A central bank or regulator may effectively lead the transition by shifting adoption incentives, e.g., through CBDC rollout, subsidies, interoperability standards, or acceptance mandates.	Changes in intercept-type incentives and/or effective decay and reinforcement terms, thereby altering both the speed of convergence and the long-run adoption level.
Regime switching	Payment system regulators; payment system operators	A threshold $G_L > 0$ separates regimes: for $G < G_L$, cashless leads (Stackelberg); for $G \geq G_L$, both instruments are established (Nash). Economically, G_L reflects minimum consumer trust in digital payments or sustainability thresholds for cash infrastructure. With closed-loop switching at $G = G_L$, if $\delta > k_2\alpha_N$ and $\delta > k_2\alpha_S$, both regimes are locally stable. If $G_\infty^S > G_L > G_\infty^N$, cyclic switching arises, with repeated exits from the Nash regime.	Capturing more detailed evolutionary trajectories: digital providers drive adoption through infrastructure investment and innovation, while cash – lacking strategic agency – responds passively yet maintains resilience.

Note: own elaboration.

Table A.1

Sensitivity analysis to net effect $k_i = a_i - b_i$ across Finland, Germany and Italy.

Country	$k_1 = k_2$	u_2^∞ (β fixed)	G_∞ (β fixed)	β (recalibrated)	G_∞ (recalibrated)
Finland	0.6	0.463	0.518	0.446	0.726
	0.8	0.608	0.806	0.325	0.968
	1.0	0.810	1.210	0.204	1.210
	1.2	1.113	1.816	0.083	1.452
	1.4	1.620	2.828	−0.038	1.694
Germany	0.6	0.149	0.329	0.139	0.462
	0.8	0.241	0.512	0.062	0.616
	1.0	0.370	0.770	−0.016	0.770
	1.2	0.562	1.154	−0.093	0.924
	1.4	0.884	1.798	−0.170	1.078
Italy	0.6	0.106	0.304	0.097	0.426
	0.8	0.191	0.472	0.026	0.568
	1.0	0.310	0.710	−0.046	0.710
	1.2	0.487	1.064	−0.117	0.852
	1.4	0.784	1.658	−0.188	0.994

Note: sensitivity analysis: net effects k_i variations. s values: Finland 0.81, Germany 0.37, Italy 0.31. All scenarios satisfy stability conditions.

CRediT authorship contribution statement

Paolo Bartesaghi: Conceptualization, Data curation, Formal Analysis. **Edoardo Beretta:** Conceptualization, Data curation, Formal Analysis. **Marco Desogus:** Conceptualization, Data curation, Formal Analysis. **Ralf Korn:** Conceptualization, Data curation, Formal Analysis.

Declaration of competing interest

None.