Physical Vectorial Monetary Systems : Framework for Eco-Social Complementary Currencies

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Paper type: Academic Research Paper

Keywords: Complementary currency; Community currency; Multi-criteria accounting; Mutual credit; Time-based currency; Ecological footprint; Agent-based simulation; Eco-social monetary design; Vectorial Monetary; Post-Growth Paradigm

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Abstract

Complementary currencies have proliferated for four decades — LETS, time banks, mutual-credit B2B circuits such as WIR and Sardex, and convertible local currencies with ecological criteria such as the Eusko and Chiemgauer. Across this design space, the unit of account remains scalar — including time-based currencies, where the unit is a one-dimensional measure of labour. Ecological criteria, where present, operate as external filters bolted onto a scalar unit; no documented complementary currency embeds multi-dimensional information inside the unit of account itself.

The standard defence of scalar money is that it is neutral — a passive medium of exchange. We argue this neutrality is illusory: existing units of account encode growth-imperative and externalisation choices into their structure. VECTOR is also non-neutral, but its non-neutrality is explicit and embedded — regulatory mechanisms are part of the unit, so the system self-regulates within parameters set once at the design layer.

VECTOR is a design framework for a complementary currency in which the unit of account is a vector across ten physical components, all treated on equal conceptual footing: time (in labour-hours), water, energy, fossil fuel, surface, renewable resources, non-renewable resources, waste, pollutants, and durability. Three mechanisms structure the design: cumulative resource accounting along supply chains (the *Contamination Principle*); a dynamic conversion rate Rate_v(t) responsive to observed flows, which translates ecological components into the time component for settlement; and a Universal Daily Income denominated in time. Conceptually, VECTOR operationalises the weak-comparability tradition of ecological economics (Martínez-Alier, Munda & O'Neill 1998) inside the unit of account itself rather than in deliberative decision processes.

We probe the framework with an agent-based simulator — five hundred heterogeneous agents over five simulated years, with sensitivity analysis on rate parameters and population composition. Under non-strategic transaction patterns, the simulation produces a bounded wealth distribution between a UDI floor and a reconciliation-driven ceiling, automatic dampening of activities targeted by an elevated rate, and convergence of monetary creation and destruction within two to three years. Findings are preliminary.

The paper contributes a complementary-currency design where ecological accounting is internal to the unit of account rather than external, opening a design space distinct from existing scalar

approaches.

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1. Introduction

1.1 Problem statement

Complementary currencies are a four-decade-old field with hundreds of active systems. Seyfang and Longhurst (2013a) map 3,418 projects across 23 countries; Blanc (2011) groups them into four generations — LETS, time exchanges, convertible local currencies, and multiplex designs. One structural feature recurs across almost every documented case: the unit of account is scalar. Mutual-credit B2B circuits (Sardex, WIR), convertible local currencies (Chiemgauer, Eusko, Bristol Pound), and time-based currencies (Cahn 2000) all operate on a one-dimensional unit. Where ecological criteria are present, they appear as eligibility filters bolted onto a scalar unit; no documented complementary currency embeds multi-dimensional resource information *inside* the unit of account.

The standard defence of scalar money is that it is neutral — a passive medium of exchange. We treat this defence as the central puzzle. A unit of account that reduces every dimension of value to a single number is not neutral: it encodes the assumption that every form of value can be expressed on one common measure — an assumption ecological economics has critiqued for three decades (Martínez-Alier, Munda & O'Neill 1998; Spash 2020). Scalar money's non-neutrality is implicit: it lives in market prices, externalisation pathways, and the growth-imperative that monetary debt produces. The question is therefore not whether to have a non-neutral unit — every unit is non-neutral — but whether non-neutrality should remain implicit or be made *explicit* and embedded in the unit itself.

A second structural feature follows. In scalar systems, the unit attached to a good is the outcome of cost accounting, market negotiation, financial structure, and imposed margins. In a vectorial system, the unit attached to a good is the cumulative physical resource actually consumed in its production. VECTOR replaces price formation with resource accounting: the unit reports reality rather than negotiating it.

A natural follow-up objection is operational: where does the multi-dimensional data come from? The framework distributes the ten basis components across four data tiers — five vectors derive from documents firms and households already maintain (timesheets, utility invoices, fuel receipts, land registries); two more from invoices combined with conversion tables; one (durability) from existing operational proxies; only two (waste, pollutants) require instrumentation beyond current routine, and regulatory frameworks (REACH, ISO 14001) supply partial documentation there. Annex F develops the tier mapping per component.

The objective is to integrate, in the very structure of the project, preventive mechanisms against the drifts of scalar monetary systems — hoarding, ecological over-exploitation, exclusion, runaway concentration of wealth, externalisation, rentier extraction, opacity. Each drift is countered by a specific construction: no compounding plus no rent income (hoarding, concentration, rentier extraction); the dynamic conversion rate (over-exploitation, externalisation); UDI plus the contribution coefficient (exclusion); the Contamination Principle plus the durability component (opacity, planned obsolescence). The approach builds a system whose combination of mechanisms prevents the drifts structurally, rather than relying on post-hoc correction not necessarily oriented toward homeostasis.

1.2 Research question

This paper asks:

> *Can a vectorial accounting unit, embedded in a mutual-credit complementary currency with a dynamic conversion rate, internalise ecological externalities and produce bounded wealth distribution under non-strategic transaction patterns?*

Three sub-questions decompose it. **Q1** — Does cumulative resource accounting along a supply chain produce informational gains over scalar pricing? **Q2** — Does the conversion-rate feedback loop stabilise aggregate ecological balances in simulation? **Q3** — How do VECTOR's mechanisms map onto existing complementary-currency designs?

1.3 Contribution and epistemic stance

The paper makes three contributions. **Theoretical**: it operationalises the weak-comparability tradition (Martínez-Alier, Munda & O'Neill 1998) inside the unit of account itself, rather than alongside it in a deliberative process. **Computational**: it develops an agent-based simulator with 500 heterogeneous agents over five simulated years; preliminary computational illustration appears in Annex E. **Design**: it presents a complete framework — ten physical components, the *Contamination Principle*, a dynamic conversion rate, a Universal Daily Income, and an equity layer with mutual credit, UDI, and a contribution coefficient — as a *design space*, not a turnkey proposal.

Epistemic stance. The paper's contribution is a specified artefact — a framework — not an empirical claim about a deployed system. The framework is designed to make a particular problem (the implicit non-neutrality of scalar money in ecological and equity terms) and a possible response (multi-criteria accounting with adaptive conversion and contribution-weighted credit) visible, examinable, and contestable. The simulator does not validate the framework; it probes its internal consistency under one set of non-strategic behavioural assumptions. Parameter ranges are illustrative defaults from which a deploying community would diverge. What the paper argues is that VECTOR is a *coherent design space worth pursuing*, not that it is a finished product nor that any particular calibration is correct. The empirical question of whether deployed instances achieve their stated objectives can only be answered by pilots; §11 sketches that agenda. The body of the paper presents the framework in conceptual prose; the formal derivations, propositions, and worked examples are developed in the annexes (G and H) with commentary suitable for verification.

1.4 Paper structure

§2 reviews three literature streams. §3 defines the framework. §4 traces how the mechanism operates across four time scales — real-time transactions, daily reconciliation, annual rate adjustment, long-term capital amortisation. §5 develops the ecological-feedback dynamics. §6 covers the equity architecture (mutual credit, UDI, contribution coefficient). §7 sketches the distributed infrastructure. §8 reports the simulation study. §9 maps VECTOR onto five reference systems. §10 discusses limitations and deployment-level falsification. §11 concludes. Annexes A–H carry the formal details: abaque (A), simulation parameters and code architecture (B), sensitivity-sweep grid (C), monetary-balance derivation (D), computational illustration with six figures from a 500-agent five-year run (E), data-tier mapping and ten-component unit (F), formal definitions and worked example (G), and enterprise mechanics with cost-recovery and amortisation (H).

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2. Literature review

This section locates VECTOR in three streams. The first — complementary and community currencies — is the field's home territory. The second — ecological economics and multi-criteria value — supplies the conceptual case for treating value as irreducibly multi-dimensional. The third — computational accounting and agent-based finance — supplies the formal substrate.

2.1 Stream A — Complementary and community currencies

Blanc's (2011) four-generation typology (LETS and time exchanges, convertible local currencies pegged to national fiat, multiplex designs) maps the field; Blanc (2017, 2018) extends it into a Polanyi-anchored conceptual framework that names a "practical criticism of commensurability" as a defining trait of alternative currencies — authorising VECTOR's multi-criteria stance from inside the field. North (2007), Lietaer (2001), Greco (2009), Fare & Ahmed (2017), Fare & Pottier (2025) provide complementary historical, practitioner, and political-economy accounts.

Two empirical traditions populate the typology. **Macro-financial stability in mutual-credit B2B circuits**: Stodder (2009) and Stodder & Lietaer (2016) show that the eighty-year-old WIR network expands counter-cyclically when Swiss-franc liquidity contracts; Sardex is documented institutionally by Littera, Sartori, Dini & Antoniadis (2017), Sartori & Dini (2016), and Dini & Kioupkiolis (2019). These accounts converge: stability comes from mutual-credit clearing plus trust-building governance, not from the unit of account, which remains scalar and euro-pegged. **Grassroots sustainability**: Seyfang & Longhurst (2013a, 2013b) document 3,418 community-currency projects; the most-developed European cases — Chiemgauer (Gelleri 2009), Eusko (Edme-Sanjurjo et al. 2020), Bristol Pound (Marshall & O'Neill 2018) — couple merchant-level participation criteria with scalar units pegged 1:1 to fiat. Fare & Ahmed (2017) and Michel & Hudon (2015) review what these designs achieve: robust social-economy effects, modest economic effects, rare or unmeasured environmental effects. Ecological intent at the eligibility stage is rarely translated into ecological information at the transaction stage.

Time-based currencies (Cahn 2000; Collom 2011; Jacob et al. 2004) are the only family in which the unit departs from scalar fiat: time is measured in physical hours of co-production. From VECTOR's perspective this is a single-component precedent — labour-hours — that the framework retains as one of ten components and supplements with nine ecological ones. Larue (2020, 2022, 2025) supplies the critical foil; §10.1 engages his critique frontally.

Across the stream — LETS (Williams 1996; Schraven 2001), time banks, B2B mutual credit, demurrage currencies (Kennedy 1995), convertible local currencies, and Global South digital community currencies (Diniz, Cernev & Nascimento 2020) — every system operates on a scalar unit. Ecological criteria, where present, are external eligibility filters.

2.2 Stream B — Ecological economics and multi-criteria value

The case that value is irreducibly multi-dimensional precedes any specific currency design. Georgescu-Roegen (1971) established that economic production necessarily increases entropy in the biosphere. Daly (1991) and Daly & Farley (2010) translate this into steady-state economics: accounting must be biophysical, not monetary. Costanza et al. (1997, 2017) attempt the inverse — monetising ecosystem services — but their twenty-year retrospective concludes that monetary valuation alone has failed to drive governance.

Martínez-Alier, Munda & O'Neill (1998) supply VECTOR's theoretical anchor. They distinguish *strong commensurability* (every value reducible to a single scalar) from *weak comparability* (values ordinally comparable across irreducibly distinct criteria), arguing that strong commensurability is incoherent and that ecological economics needs a multi-criteria foundation. Martínez-Alier (2002) develops the political consequence: environmental conflicts are conflicts between "languages of valuation". Spash (2020) distinguishes a "new resource economics" wing retaining scalar willingness-to-pay from a "social-ecological economics" wing rejecting it; VECTOR sits on the latter.

Applied design has approached the same problem from the other side. Raworth (2017) frames economic activity as a corridor between social floor and planetary ceiling, both in physical units. Jackson (2017) argues that growth–impact decoupling at the required rate is empirically implausible. Helbing (2014) is the closest mechanism-level precedent: "qualified money" carrying reputational attributes with differential conversion rates. Two differences from VECTOR: Helbing's qualities attach to *agents*, while VECTOR's components are physical quantities attached to *resources*; and Helbing's mechanism is conceptual, while VECTOR specifies a basis, propagation rule, and feedback dynamic.

The stream supplies the *why* but not the *how*. Ecological economics has argued for thirty years that value is multi-dimensional, but has not delivered an operational unit of account on which transactions can clear.

2.3 Stream C — Mathematical and computational foundations

Two engineering literatures anchor the formal substrate. **Accounting ontology**: McCarthy's (1982) Resource–Event–Agent (REA) model proposes building accounting systems on shared semantic primitives — resources, events, agents — rather than journal entries. ValueFlows (W3C community specification) operationalises REA for federated cooperative networks. The data model VECTOR requires fits this tradition; what the tradition has not done is attach the vector to a *currency* mediating exchange and against which mutual-credit balances are kept.

Agent-based computational economics: Cincotti, Raberto & Teglio (2010) and the Eurace family simulate whole credit-money economies with heterogeneous agents; LeBaron (2006) provides the methodological canon. Fleischman, Dini & Littera (2020) supply obligation-clearing graph algorithms; their Sardex analysis shows obligation-clearing reduces SME net internal debt by ~25 %, doubled to ~50 % with a mutual-credit liquidity source — empirical anchor for VECTOR's balance-at-zero claim. Pinheiro & Pinheiro (2025) provide the most direct mathematical antecedent: money as a rank-1 tensor over (sector, agent, time). VECTOR specialises this tensor onto an ecological basis and adds the dynamic conversion rate. The Lietaer–Ulanowicz lineage (Lietaer, Ulanowicz, Goerner & McLaren 2010; Lietaer et al. 2012) bridges Streams B and C.

2.4 Gap statement

Across the three streams, no documented complementary currency embeds multi-dimensional physical accounting inside its unit of account, no ecological-economics design proposal operationalises weak comparability at the transactional level, and no REA-derived accounting system functions as a circulating mutual-credit currency with an endogenous conversion rate. **VECTOR occupies the intersection of these three absences.**

3. Framework: definitions and design choices

3.1 The ten-component unit of account

The unit of account is a vector with **ten components**, each carrying a distinct physical unit. The components, listed in order:

1. **Time** — in hours of labour-time
2. **Water** — in m^3
3. **Energy** — in kWh
4. **Fossil fuel** — in m^3 at 15 °C
5. **Surface** — in m^2·day
6. **Renewable resources** — in m^3 or kg per material class
7. **Non-renewable resources** — in m^3 or kg per material class
8. **Waste** — in m^3 or kg per disposal class
9. **Pollutants** — in m^3·toxicity or g per substance class
10. **Durability** — dimensionless ratio (MTBF / MTTR)

The ten components are treated as **equal-dignity axes of the unit**: a transaction, a ledger entry, or an inventory record carries values on all ten, each in its own physical unit. The arithmetic on the vector is component-wise: there is no metric or distance between components, no exchange ratio at the level of basis, no privileged component. Annex F gives the full Table 1 with documentary source per component and the four-tier data-availability mapping (A: existing routine accounting; B: invoices + conversion tables; C: existing operational proxy; D: emerging instrumentation).

Each component is **signed** under a uniform convention: `v_j > 0` records that the agent has *produced* or *regenerated* the resource on their ledger (biogas created by a methaniser, waste recovered, hours of labour credited to a worker as part of an exchange); `v_j < 0` records that the agent has *extracted from nature* or *absorbed an ecological debt* (raw-material extraction, pollution emission, hours of labour debited from an employer who paid workers). The convention is cognitively uniform across all ten components — a reader identifies production versus extraction from the sign alone. Transactions transfer signed components: a vendor selling extracted material transfers a negative `delta_v` (the ecological debt moves down the supply chain to the next agent), a vendor selling regenerative goods transfers a positive one. The basis is not a universal claim: a community may add an animal-welfare or biodiversity component, or modify material-class aggregation, at the design layer (§3.5).

Time (component 1) carries the same accounting structure as the other nine — it is signed, transferable, recorded on agent ledgers — and it has, in addition, two mechanisms that the others do not: it serves as the conversion target for the other nine components (§3.3), and it carries the Universal Daily Income (§3.4). These mechanisms are *additional rules attached to component 1*, not a different conceptual status of time relative to the other components. The signed convention, the inventory accounting, the transfer mechanics, and the Contamination Principle apply uniformly across the ten.

3.2 The Contamination Principle

When a transaction occurs along a supply chain — agent a_1 produces an input, a_2 transforms it, a_3 buys the finished good — the vectors accumulate rather than cancel. Each step in the chain contributes a *step-vector* recording the resources extracted, transformed, or regenerated at that step. The cumulative vector reaching the buyer is the component-wise sum of all step-vectors along the chain. The vector follows the good through every transformation.

We call this the *Contamination Principle*: every transformation carries its cumulative resource history forward. Two consequences. First, the value reaching the buyer aggregates the entire upstream chain — comparison across competing producers is valid because each cumulative vector aggregates the full path. Second, the cumulative accounting creates a continuous incentive to seek lower-impact suppliers: a producer can lower their output vector by sourcing from lighter-footprint upstream actors, and the improvement is immediately visible in the producer's own accounting. The mechanism does not prohibit externalisation; it routes producer choice toward lighter suppliers by making the upstream load part of the producer's accounting. Annex G states the formal path-sum identity, the joint-production allocation rule (Hauschild, Rosenbaum & Olsen 2018), and presents a worked example (woodcutter and carpenter).

3.3 The conversion mechanism

To enable daily settlement on a mutual-credit substrate, the framework introduces an asymmetric conversion of the nine ecological components into the time component. For each ecological component $v \in \{2, \dots, 10\}$, a **base rate** $R_v > 0$ (set at the design layer) and a **pressure index** $I_{p,v}(t) \in [\alpha_v, \beta_v]$ (dynamically computed each year from observed flows) together give the **current conversion rate**:

$$\mathrm{Rate}_v(t) := R_v \cdot I_{p,v}(t).$$

Verbally, $\mathrm{Rate}_v(t)$ is the labour cost the system requires to redeem one physical unit of consumption on component v: "to redeem 1 m^3 of water consumed, the agent must spend $R_{water} \cdot I_{p,water}(t)$ hours."

Three structural properties characterise the conversion. **(P1) Asymmetry of the mapping.** The conversion is defined only from components 2–10 to component 1 (time). The reverse is not defined — time does not convert to water, energy, etc., except indirectly through someone choosing to produce a resource by spending labour (which is then transferred via ordinary mutual-credit, not via

`Rate_v`). **(P2) No ecological-to-ecological mapping.** No rate converts water into energy, energy into surface, or any pair of ecological components into one another. Ecological units become exchangeable only via the time component — never directly with one another. This carries the regulatory load: tightening `Rate_v(t)` on a single component raises the labour cost of that component without making it convertible into any other ecological axis. **(P3) Bounded pressure-index range.** Each `I_{p,v}(t) ∈ [α_v, β_v]` with `0 < α_v ≤ β_v < ∞`; `α_v > 0` is a framework invariant that prevents `I_p` from collapsing to zero and erasing the regulatory effect.

The same numerical `Rate_v(t)` operates in three contexts during the operational year: as the *settlement factor* at daily reconciliation (§4.2), where it converts accumulated ecological flows into time-axis credits or debits; as the *redemption factor* an agent may use voluntarily to clear an ecological balance before daily reconciliation; and as the *informational scalar valuation* at the transaction window, where the multi-component vector of a competing offer is aggregated into a single time-equivalent for buyer comparison, without committing to any settlement (the multi-component vector remains on the ledger).

The functional form of `I_{p,v}(t)` — how the pressure index responds to observed flows — is the framework's automatic regulation mechanism, developed in §5.

The choice of time (rather than energy or a composite eco-weighted index) as the conversion target rests on three design grounds: time's universality across all human exchange (every transaction can be expressed in labour-time equivalent); time's natural alignment with mutual credit and with the UDI mechanism (§3.4); and the three-way human-day partition (8 h sleep, 8 h work, 8 h community life) that motivates the `Δt = 8 h` UDI cap.

3.4 Equity layer: mutual credit, UDI, contribution coefficient

VECTOR builds on a mutual-credit substrate (Greco 2009; Stodder 2009): ordinary transactions clear as matched credit/debit pairs on the time component, with no net change in the money stock. WIR and Sardex have demonstrated empirically that mutual credit carries activity without an issuer and without interest (Stodder & Lietaer 2016; Littera et al. 2017); VECTOR inherits this at the transactional layer and adds three mechanisms operating on the time component (the "additional rules" of §3.1).

Universal Daily Income (UDI). A daily entitlement of up to `Δt = 8 h` on the time component, demand-driven: UDI compensates the day's outflows (extractive consumption + labour paid by producer) first, and any residual within the `Δt` cap flows to debt clearance when the agent's time-component balance is negative. UDI is monetary creation (no matching debit). An agent with no outflows and a non-negative balance receives no UDI that day. **Signed conversion reconciliation** (§3.3). At day's close, accumulated ecological inventory on a consuming agent's ledger converts to time and is added to the time-axis balance, signed — regenerative consumption credits, extractive consumption debits. **Contribution coefficient** `q_w ∈ (0, 2]`. When worker `w` performs `X` hours of labour, `w`'s balance is credited `q_w · X` while the employer's is debited `X`; the resulting asymmetry `(q_w − 1) · X` between the credit and the debit is monetary creation if `q_w > 1` or destruction if `q_w < 1` — not posted to any separate ledger but visible only as the community-wide aggregate.

The three operate at different cadences (UDI daily; conversion daily for final consumption or at sale-time for inventoried stock, §4.4; `q_w` whenever labour is exchanged) and together constitute the equity architecture: UDI provides the floor, `q_w` provides the upward path, and the absence of compounding provides the upper boundary. §6 elaborates. `Δt = 8 h` is a framework invariant (three-way human-day partition: 8 h sleep / 8 h work / 8 h community); `q_w ≤ 2` is invariant; the abaque is community-set and revisable by two-thirds supermajority (Annex A).

3.5 Two governance layers

The framework distinguishes a **design layer** (parameters the community deliberates and votes on: the ten-component basis, the base rates `R_v` per ecological component, the functional form of `I_p(t)`, the UDI cap and priority-of-use rules, the abaque governing `q_w`, and the governance procedures themselves) and an **operational layer** (the transactions). Once design parameters are set, the operational layer self-regulates through `Rate_v(t)` responding to observed flows; calculation rules are transparent and known to every participant but not directly adjustable in the course of a transaction.

Non-neutrality as explicit delegation. The phrase "self-regulates" warrants precision. The framework's non-neutrality — the directional pull of `Rate_v(t)` toward ecological dampening, of the abaque toward community-recognised contribution, of mutual credit toward zero-sum clearing on the time axis — is determined politically at the design layer through community deliberation. Once those parameters are fixed, the operational layer enacts the chosen non-neutrality without further political intervention. The non-neutrality is not laundered through operational autonomy; it is *explicit, deliberately chosen, and structurally delegated*. What VECTOR removes is the *implicit* non-neutrality of scalar money — the growth imperative encoded in interest-bearing debt, the externalisation pathways embedded in market pricing, the rentier extraction naturalised as "return on capital" — and substitutes a non-neutrality that is visible, adjustable, and accountable to a deliberative process.

The design layer is itself bounded by **framework-level invariants** the community cannot vote away: `R_v > 0`, `α_v > 0` with `β_v − α_v ≥ 0.05`, `Δt = 8 h`, the asymmetry of the conversion mapping (only components 2–10 convert to component 1; no ecological-to-ecological), and `q_w ≤ 2`. A community wanting different values must instantiate a non-interoperable instance. The framework is *adaptive yet non-corruptible*.

3.6 What VECTOR is not

VECTOR is *not* a fiat replacement. It is a complementary currency in the Blanc (2011) sense — operating alongside national currencies. VECTOR is *not* a Hayekian project. The argument is not that competing private currencies will discipline state issuers; it is that a community can deliberately design a unit of account that internalises ecological information. VECTOR is *not* a turnkey proposal. Components can be implemented one at a time — starting with Tier A (time, water, energy, fossil fuel, surface) — so adoption proceeds incrementally.

VECTOR is *not* a pricing mechanism. The vector attached to a good is the physical resource it actually consumed or produced under the §3.1 signed convention. There is no markup, no equity provisioning, no rentier extraction embedded in the unit. What the community chooses to do with that information — how to weight extraction via `R_v`, how to redistribute through `q_w` — is design-layer politics, not pricing. A consequence on the production side: an enterprise cannot accumulate profit on its time-axis balance. Labour paid to workers debits the enterprise; sales credit it through cost-recovery pricing (§4.4 and Annex H); the ecological footprint travels with the goods as signed components and reconciles on the consuming household's ledger, not on the enterprise's. Over a production-sale cycle the enterprise's balance returns to neutrality by construction; a persistent negative drift signals demand failure (overproduction relative to market), not profit extraction. Enterprises are pass-through transformation entities — they emerge as such from the same vector-accounting rules that apply to all agents, not from a separate regulatory regime.

4. Operational mechanics across time scales

The framework's mechanics run at four interlocking time scales. **Real-time** for transactions (any moment, two agents exchange goods or labour). **Daily** for the reconciliation of accumulated ecological flows into the time component on the consumer-side of the chain. **Annual** for the rate adjustment that maintains the framework's monetary balance. **Long-term** for capital amortisation through cost-recovery pricing on the production side. The formal recursions, definitions, and full operational details are given in Annex G (formal definitions and worked example) and Annex H (enterprise mechanics, cost-recovery, amortisation).

4.1 Real-time: transactions

At any moment, two agents may transact. A transaction transfers signed vector components between their ledgers, component by component. A sale of a good with cumulative resource content `V_total` transfers `V_total` from the seller's inventory to the buyer's inventory — the time component (`V_total[1]`) covering the labour content transferred to the seller as positive credit on time, the ecological components (`V_total[2..10]`) carrying the eco-footprint as signed components in the buyer's inventory. A labour transaction transfers hours on the time component only (with `q_w`-weighted credit on the worker side, Annex G). Multi-step supply chains accumulate vector components along the chain per the Contamination Principle (§3.2). Real-time transfers are mutual-credit balanced — what one ledger gains, another loses on the same component.

The real-time layer does not, in itself, alter the money stock. Money creation and destruction happen at later layers (daily reconciliation, annual re-calibration, q_w-weighted credit).

4.2 Daily: ledger reconciliation for consuming agents

At day's close, agents whose accumulated inventory represents *final consumption* — households consuming food, water, energy for daily living — reconcile their ecological flows. The magnitude on each ecological component is converted to time-equivalent via `Rate_v(t_n)` and added to the time-axis balance, preserving sign. A negative ecological inventory (extractive consumption absorbed) produces a negative time-axis contribution (debit); a positive ecological inventory (regenerative consumption absorbed) produces a positive contribution (credit). In compact form (formal definitions in Annex G):

```
    Δθ_a^{conv}(n) := Σ_{j=2}^{10} Rate_j(t_n) · v_{a,j}(n)
```

where `v_{a,j}(n)` is the agent's signed inventory on component `j` accumulated over day `n`, and `Δθ_a^{conv}(n)` is the resulting net time-axis change at reconciliation.

Universal Daily Income then credits the time-axis balance. Let `S_a(n)` denote the day's outflows (labour paid plus the magnitude of any negative `Δθ_a^{conv}(n)`) and `D_a(n) := max(0, −θ_a(t_{n−1}))` denote the agent's current time-component debt (positive when in debt, zero otherwise). UDI adds

    U_a(n) := min(Δt, S_a(n) + D_a(n))

to the time-axis balance — bounded by `Δt = 8 h`, demand-driven (capped at outflows + debt). UDI compensates the day's outflows first; any residual within the `Δt` cap flows to debt clearance when the agent is in debt. An agent with no outflows and no debt receives zero UDI that day. UDI is monetary creation on the time component: no offsetting debit anywhere.

Daily reconciliation fires only on the ledger of the agent who finally consumes the resource. Enterprises producing goods destined for future sale hold work-in-progress as signed inventory and do not reconcile at day's close: their ecological components persist as raw inventory until the goods are sold, at which point they transfer to the buyer's ledger and reconcile *there*, at the buyer's next day's close. The enterprise's time-axis balance is driven only by ordinary mutual-credit transfers — worker payment (debit) and sale (credit through cost-recovery pricing, Annex H) — so over a production-sale cycle it returns to neutrality by construction. The new agent receives a one-time endowment of `Δt` hours on the time component at enrolment.

Time-axis debt (`θ_a < 0`) arises when daily outflows exceed `Δt` and accumulate without sufficient inflows. Debt clears through three channels: labour given to the community (one-for-one credit on `θ_a`); consumption of regenerative goods (positive `Δθ_a^{conv}` credits `θ_a` directly); and residual UDI, applied within the daily `Δt` cap after outflow compensation. Two illustrative cases: an agent in debt who incurs no outflows on day `n` receives `U_a(n) = min(Δt, |θ_a(t_{n−1})|)` of UDI flowing entirely to debt-paydown (a `−200 h` debt clears at `Δt = 8 h/day` over 25 idle days). An agent in debt whose outflows exceed `Δt` exhausts the UDI on outflows and the excess accrues to debt — the cap binds either way.

4.3 Annual: rate adjustment and re-calibration

Once per operational year, two mechanisms run. First, the **pressure indices** `I_{p,v}(y+1)` are recomputed for each ecological component from the year's monthly aggregates and the equilibrium trajectory the community has set at the design layer. The mechanism is *memoryless piecewise-linear with dead band*: deviations within `[−δ_v, +δ_v]` leave `I_p` at 1; deviations outside push `I_p` up or down with slope `s_v`, clamped to `[α_v, β_v]`. Second, the **base rates** `R_v` are recalibrated by a damped factor `√(B/D_destroyed)` to maintain monetary balance — bringing total monetary creation `B` (UDI + `q_w`-net + regenerative credits) in line with total monetary destruction `D_destroyed` (signed-conversion debits) across the community. Both adjustments are framework-proposed and community-ratified through the continuous-polling governance system (§7.3). Full formal derivation, year-0 initialisation, and the equilibrium trajectory definition appear in Annex D.

A safety mechanism — the **homeostatic proposer** — fires when a vector's `I_p` approaches saturation (`I_{p,v}(y+1) > α_v + 0.95 · (β_v − α_v)`): the framework computes a minimal `(β_v, R_v)` adjustment that returns projected `I_p` to the dead band and posts it as a community-ratifiable proposal. The proposer's logic is transparent and deterministic — any participant can re-derive the proposed adjustment from public state. The framework is the *proposer*; the community is the *ratifier*.

4.4 Long-term: capital amortisation through cost-recovery

Capital goods (machinery, equipment, buildings) enter the framework through the same transactional mechanics as any other good: when enterprise A buys a machine from enterprise B for `X` hours of labour-content, A's time-axis balance decreases by `X` and B's increases by `X` — ordinary mutual credit on component 1. The machine carries a non-zero cumulative footprint on the ecological components, which transfers to A's inventory as signed components.

To recoup the labour cost paid for the machine, A includes the machine's labour content in its cost-recovery pricing of the products it goes on to produce. The machine's labour cost adds to a running labour-recovery counter at A's level, which the cost-recovery rule recoups over A's subsequent sales (formal definition in Annex H). The result is that capital labour content propagates downstream into the products that use the capital, via the Contamination Principle (§3.2) — the cumulative vector of a piece of bread includes its share of the oven's labour content, amortised over the oven's productive lifetime. A's time-axis balance returns to neutrality over the amortisation horizon, provided pricing is set to fully recoup the inputs.

Two design-level constraints govern long-term capital flows. First, *individual ownership* of physical assets is allowed, but *commercial property income* is not: rent on a rented asset is calculated as construction-and-maintenance cost amortised over `n` years, with no profit margin embedded — the period `n` is set at the design layer to match the asset's expected useful life (typically decades for buildings and land, shorter for machinery and furniture, calibrated by asset class). Second, *enterprise surplus* — the accumulated time-axis balance at an enterprise — is consumable only by future enterprise investment, never by individual withdrawal. The two constraints together remove the principal capital-accumulation channels of conventional money while preserving everyday personal-asset ownership.

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5. Ecological feedback: rate dynamics

The annual `I_p` adjustment of §4.3 is the framework's automatic regulation mechanism. This section develops the rationale and the parameters; the formal derivation is in Annex D.

5.1 Cadence and equilibrium trajectory

The cadence is annual: `I_{p,v}` is recomputed once per operational year and held constant through the next. Three motivations: ecological time scales (water-table recharge, soil regeneration, carbon balance all operate annually or longer), capital adaptation realism (decisions are not reconfigured monthly), and governance rhythm (continuous polling aggregates over the year and applies at year-close deadlines, §7.3). The mechanism is memoryless: each year's `I_p` is computed from that year's deviation alone, with noise absorbed by a 12-month moving-average smoothing pipeline.

The system maintains monthly aggregates `F_v(m)` (consumption, the positive-magnitude part of extractive flows under §3.1) and `G_v(m)` (regeneration). At year close, the *equilibrium trajectory* is

`T_v(y) = (1 − λ_v) · MA_{12}(F_v − G_v)(y) + λ_v · D_v(y)`,

combining the trailing 12-month mean with a monetary-balance target `D_v(y) = F_v(y−1) · (B(y−1) / D_destroyed(y−1))`. **No external sustainability number is required** — the equilibrium emerges internally from monetary stability rather than from planetary-boundary estimates. Annex D develops the derivation.

5.2 Annual adjustment

At year `y` close, the relative deviation `d_v(y) := (F_v(y) − G_v(y) − T_v(y)) / T_v(y)` drives the next year's pressure index via a piecewise-linear update with dead band `δ_v` and slope `s_v`, clamped to `[α_v, β_v]`. The systematic `R_v(y+1) := R_v(y) · √(B(y)/D_destroyed(y))` re-calibration applies to all `v ∈ {2, …, 10}` independently of the `I_p` update — the over-exploitation proposer handles acute saturation within a year, the systematic re-calibration handles slow drift across years. Both are framework-computed proposals subject to community ratification.

Five community-set parameters per component (`δ_v`, `s_v`, `α_v`, `β_v`, `λ_v`) define the response function; five framework invariants (§3.5) bound the parameter space.

5.3 Calibration and stability

The homeostatic structure — over-consumption raises the rate, raised rate lowers consumption, lowered consumption brings the system back toward the trajectory — favours convergence over divergence. Large-scale oscillation is structurally unlikely under the smoothing pipeline (12-month MA, annual cadence, dead band, saturated slope). §8 quantifies parameter sensitivity computationally; §10 returns to falsification.

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6. Equity architecture: mutual credit, UDI, contribution coefficient

§4 located UDI, signed conversion, and `q_w`-weighted credit as three mechanisms operating on the time component at different cadences. This section completes the equity architecture by detailing each, by stating the wealth-bound claim that emerges from their combination, and by presenting the diagnostics the community uses to monitor equity. A footnote at the close discusses reproducible digital goods.[^digital-goods]

The perspective is structural rather than redistributive. VECTOR does not transfer wealth from rich to poor by direct policy. It removes the channels through which scalar money concentrates wealth without bound — interest on positive balances, rent as commercial income, capital gains, compounding debt — and substitutes mechanisms that reward contribution while subsidising basic participation.

Property and rent. Individual ownership of physical assets — apartments, houses, land — remains entirely possible under VECTOR. What is removed is the *commercial property income* channel. Where the owner rents the asset, rent equals construction-and-maintenance cost amortised over 99 years (total cost ÷ 99 ÷ 12 per month, plus the period's maintenance). After 100 years the construction term has fully amortised and rent reduces to maintenance only. No profit margin; rent is cost recovery, not income. Same for land.

6.1 Mutual credit on the time component

The time component operates as a community-wide mutual-credit ledger. Every agent's time-axis balance opens at the initial endowment $\Delta t = 8\ h$, transactions clear as matched credit/debit pairs across community accounts, and the sum across the community is constant — *modulo* the three asymmetric mechanisms (UDI, signed conversion, q_w-weighted credit) introduced below. A positive balance records that the agent is a net contributor of time; a negative balance records time debt, settled through labour given.

What VECTOR adds over canonical mutual credit is twofold. First, the ledger carries not just the time-component balance but the cumulative ecological-component record of consumption per agent. Second, the time component acquires three creation/destruction channels rather than the zero of pure mutual credit.

6.2 Universal Daily Income

UDI is the unconditional equity-floor component of the architecture. §4.2 formalised the daily mechanism $U\_a(n) := \min(\Delta t,\ S\_a(n) + D\_a(n))$ with $\Delta t = 8\ h$ as a framework invariant. Three properties matter in equity terms. **Universality of entitlement**: every participant has a daily UDI capped at Δt, regardless of age, activity, or employment status — the 8-hour cap counts the community-life block of the three-way human-day partition as contribution-as-such. **Demand-driven, not unconditional accumulation**: UDI is bounded by present need — the sum of the day's outflows $S\_a(n)$ and the current debt $D\_a(n) = \max(0,\ -\theta\_a(t\_\{n-1\}))$. An agent with no outflows and a non-negative balance receives 0; an agent with outflows or a negative balance receives the smaller of Δt and (outflows + debt). UDI does not flow to a positive time-component balance: holding generates no UDI, only outflows or debt does. **Three channels for debt clearance**: labour given to the community (one-for-one credit), consumption of regenerative goods (positive $\Delta\theta\_a\text{\^{}}\{conv\}$), and residual UDI (the portion of the daily Δt cap not absorbed by current reconciliation, applied to the running debt within the cap).

The framework connects to the time-banking tradition (Cahn 2000; Collom 2011) — a daily entitlement in physical hours by virtue of being a person — while bounding the entitlement by present need (reconciliation + debt) rather than offering an unconditional cash flow that would accumulate on positive balances. The bound preserves the anti-rentier property without weakening the equity-floor effect: an agent with a positive time-component balance receives no UDI on idle days, so accumulation requires participation (rebutting the rentier-on-UDI critique of Standing 2017), while an agent in debt receives UDI applied first to current outflows and then to debt clearance — UDI thus operates as a structural debt-recovery channel within the daily cap, ensuring debt eventually clears even for agents whose capacity for labour given is limited (illness, age, caregiving responsibilities, extended unemployment).

6.3 The contribution coefficient q_w and the abaque

When agent w performs X hours of labour for agent e, w's time-axis balance is credited $q_w \cdot X$ hours while e's is debited X hours. The net flow $(q_w - 1) \cdot X$ is monetary creation if $q_w > 1$ and destruction if $q_w < 1$. The framework records labour at full physical value on the employer side and credits a community-recognised multiple of it on the worker side.

The mapping from worker profile to q_w is the **abaque** — a community-defined table of contribution components with additive structure. The illustrative baseline (Annex A) combines an age tier (one only, 0.10–0.50), an education tier (one only, +0.10–+0.80), and cumulative components (years of work, caregiving, childcare 0–7 yr, business-owner status, elected role, verified volunteer status, validated continuing education). A minimum-engaged adult (18+, bac) reaches $q_w = 1.00$; a heavily-engaged adult (doctorate, 20 years of work, caregiving, elected role, volunteer) reaches ~1.90, just under the cap ($0.1 \leq q_w \leq 2$).

Universality and inclusion. The additive structure opens the upward path to every participant, not only those excelling along academic or specialised-aptitude tracks. Multiple independent cumulative components (years of work, caregiving, childcare, elected role, volunteer status, continuing education) reward trajectories distinct from the education tier. An adult with limited education and no specialised aptitude who provides caregiving, volunteers, and accumulates years of work reaches $q_w \approx 1.05$, on par with a typically-engaged bac+3 holder; adding childcare and elected role brings the same agent to ~1.30. Sustained community engagement translates into augmented credit on every paid labour transaction.

Community validation. Components of q_w are not certified by a central authority. Each claim is recorded as a cryptographic attestation produced by community validation: the agent submits evidence with their own signature; the framework selects random third-party community members who sign attestations of veracity, with a configurable threshold for validity. Years of work accumulate from contracted labour transactions on the chain itself. Attestations have explicit validity periods. Revocation is itself an attestation subject to the same threshold. The mechanism adapts REA-derived patterns (McCarthy 1982; ValueFlows) and the W3C Verifiable Credentials Data Model (2024) to a randomised-community-validator pool; §7.2 details the operational mechanism.

Governance and political content. The abaque is more constitutional than the rate-adjustment parameters of §5. Modifying it requires a two-thirds supermajority of votes through continuous polling (§7.3) — versus simple majority for R_v, δ_v, s_v, α_v, β_v, λ_v. The framework ceiling $q_w \leq 2$ is itself invariant — no supermajority can lift it. **The abaque values are not neutral**: they encode a political choice about *what counts as contribution*. The framework supplies the mechanism (additive coefficients, attestation pipeline, ceiling, supermajority rule); the community supplies the content. A community recognising traditional ecological knowledge, mutual-aid in extended families, or specific cultural practices will populate the abaque differently from one that does not, and the framework neither prescribes nor adjudicates between these choices. The values are *deliberately exposed* to political contest at the design layer; the framework's role is to make them visible, revisable through a defined procedure, and resistant to silent capture.

6.4 The wealth-bound mechanism

VECTOR's equity claim — that wealth distribution on the time component is bounded — rests on the combined effect of the four mechanisms operating on the mutual-credit substrate: UDI (consumption subsidy floor), signed conversion (extractive consumption debited, regenerative consumption credited), q_w-weighted labour credit (upward path), and the absence of compounding. Two propositions formalise the claim (Annex G).

Proposition G.1 (defensive properties, conjectured). Under standing assumptions on UDI, daily reconciliation, bounded daily labour throughput, and non-strategic transactions: (a) no compounding term — saved hours generate no return on positive balances; (b) a consumption subsidy floor of Δt per day on outflows; (c) debt clears through three channels — labour given, regenerative consumption, and residual UDI (the portion of the daily Δt cap not absorbed by current outflows, applied to debt-paydown within the cap).

Proposition G.2 (upward path through contribution, conjectured). Under the same assumptions plus the q_w mechanism, an agent working X hours on day n with coefficient q_w gains $q_w \cdot X$ hours of credit. Framework caps $q_w \le 2$ (invariant) and $X \le 8$ (three-way human-day partition); maximum daily balance accumulation from labour is therefore $q_w \cdot X \le 16$ hours.

The combined effect: **neither extreme of inequality is achievable**. Below, the UDI consumption subsidy and linear debt-clearance through labour prevent basic deprivation. Above, the absence of compounding plus the bounded daily accumulation (16 h/day maximum from labour, never exponential) prevent runaway concentration. Wealth differentials are real and intentional — they track engagement via q_w — but grow *linearly in time*, *capped per day*, and *contingent on continued labour*. What VECTOR removes is the positive-feedback channels of conventional money: interest, rent as income, capital gains, compounding debt.

6.5 Equity diagnostics

The community monitors equity through three diagnostics computed at the close of each operational year. **Stability ratio**: the 90/10 percentile ratio of time-axis balances (target below 5) plus the share of agents in persistent debt (target below 5 %). **Resource adequacy ratio**: for each ecological component v, the ratio of D_v to net consumption $F_v - G_v$; values close to 1 indicate consumption near the monetary-balance budget. **Mean contribution coefficient** $\bar{q}(y)$: tracked year over year. A rising $\bar{q}$ reflects increasing community engagement — a measure of social-fabric strength analogous in spirit to Bhutan's Gross National Happiness index. §8 reports these for a five-year simulated horizon; §10 returns to falsification.

[^digital-goods]: **Reproducible digital goods.** A single act of production followed by indefinite costless copying does not fit the finite acyclic supply chain of §3.2: each new copy benefits from the original act without ever debiting the producer's ledger again, while the producer's initial labour is captured at the first transaction only. A retroactive-rebate mechanism (sketched in earlier work on function-based pricing, after Pelinquin) was considered but raises operational questions we have not yet researched sufficiently. We treat reproducible digital goods as a research direction for follow-up work (§11).

7. Distributed infrastructure

§4 and §6 specified the ledger semantics; this section sketches the architecture compatible with them. VECTOR does not require novel infrastructure, only the appropriate composition of established components.

7.1 Agent-centric ledgers with aggregation nodes

Each participant holds their own ledger — a private record of every transaction signed or received, with cryptographic signatures from counterparties. Transactions clear pairwise. The framework adds a **retro-verification mechanism**: each new transaction cryptographically validates the previous ten transactions of the two agents involved. Resolution is local (from the chain of signatures) or via live P2P query to previous counterparties. Retro-verification provides a per-transaction integrity check without requiring global consensus.

For community-wide aggregation, **aggregation nodes** — software components deployed voluntarily by users — autodiscover each other and assemble the aggregates required by §5 and §6.5 (flow totals `F_v(m)`, trajectory `T_v(y)`, mean `q̄(y)`, stability and adequacy ratios). No node is privileged; redundancy across overlapping subsets provides fault tolerance. The pattern follows Holochain's agent-centric distributed-hash-table model (Harris-Braun, Brock & Russell 2018).

7.2 Cryptographic attestations via community validation

§6.3's `q_w` is computed from cryptographic attestations. The agent submits evidence with their own signature; the framework selects random third-party community members who sign attestations of veracity; multiple independent attestations accumulate confidence; the claim is valid once a configurable threshold is reached. Revocation is itself an attestation subject to the same threshold. The mechanism adapts the W3C Verifiable Credentials Data Model (2024) and REA semantics to a randomised-community-validator pool — VECTOR does not assume a registry of pre-trusted institutional issuers. Disputes are handled by counter-attestation.

7.3 Two operational rhythms

Daily reconciliation: each consuming agent's ledger reconciles at day close (ecological flows aggregate, signed conversion applies via prevailing `Rate_v`, UDI is credited per §4.2). The `q_w`-weighted labour credit operates separately, at the moment of each labour transaction throughout the day, not at end-of-day reconciliation. Both are local to the agent or pairwise across counterparties; no global synchronisation. **Continuous governance, deadline-applied**: **no annual general meeting** — community members do not know each other personally. The framework software is the governance medium. Questions (abaque revisions, parameter changes, over-exploitation triggers) are posted with predetermined deadlines; members vote at their convenience; at deadline the threshold is checked (simple majority for `R_v`, `δ_v`, `s_v`, `α_v`, `β_v`, `λ_v`; two-thirds for the abaque) and the change applied automatically. The framework software is also an *active proposer*: when the §5 over-exploitation trigger fires, it computes and posts the minimal `(β_v, R_v)` adjustment as a ratifiable proposal — an automaton bounded by framework invariants and overridable by community vote.

7.4 Scalability, inter-community bridges, privacy

A canonical instance — defined by the framework invariants — interoperates with other canonical instances. A non-canonical instance (different Δt, different basis) does not bridge: there is no defensible conversion factor between two communities operating on different unit systems. VECTOR exposes aggregates, not transaction details. Selective disclosure is default. Two spot-check mechanisms limit fraud: cryptographic retro-verification (§7.1) and random P2P live verification of sampled past transactions. The required cryptographic primitives are under active implementation development.

8. Simulation study

8.1 Objective

The simulation is a constructive existence proof, not a calibration. It asks: do plausible parameter values produce trajectories in which the three §6.5 diagnostics — stability ratio, per-component adequacy, mean $\bar{q}(y)$ — remain inside tolerable ranges over a five-year horizon? Five simulated years allow four full cycles of the annual I_p update.

8.2 Model architecture

Population. Baseline $N = 500$: individuals ($N_I = 400$, 80 %), business-owners ($N_C = 75$, 15 %), enterprises ($N_E = 25$, 5 %). Approximately twelve active owners hold the twenty-five enterprises (1–2–3 distribution, median two); the remaining sixty-three business-owners participate as individuals. Enterprises are distributed across five sectors with vector-consumption profiles drawn from typical input-output coefficients: agriculture, artisanal, distribution, services / care / education, technology. Distribution: 5 / 6 / 4 / 5 / 5.

Agent ledgers and operational rules. All agents carry the same ten-component ledger structure. The distinction between individual-style and enterprise-style behaviour emerges from the *state of the inventory*: agents whose inventory represents final consumption reconcile daily; agents whose inventory represents work-in-progress (raw materials, finished stock awaiting sale) pass the ecological content through to the buyer at sale-time without reconciliation. Cost-recovery pricing maintains the enterprise time-axis balance near neutrality over each production-sale cycle; the formal mechanism is in Annex H.

Five daily phases. Each simulated day proceeds in five phases: (i) transactions under a persistent encounter graph (within-sector 0.7, cross-sector 0.15, owner ↔ enterprise 0.95); (ii) conversion-rate read for informational display; (iii) daily reconciliation on the consuming agents' ledgers; (iv) UDI flow on consuming agents; (v) aggregation push to community-wide monthly aggregates $F_v(m)$, $G_v(m)$. Annex H details the per-phase computations.

Annual closing. Past twelve months' aggregates go through the §5.2 pipeline. The systematic $R_v(y+1) := R_v(y) \cdot \sqrt{(B/D_{destroyed})}$ re-calibration applies to all components $v \in \{2, \dots, 10\}$. Voting is auto-ratified in the simulation (§8.7 limitation).

8.3 Parameters and reproducibility

The baseline configuration uses 500 agents, five-year horizon, `Δt = 8 h`, illustrative `R_v` per component (sensitivity-tested in §8.6), §5-default rate-adjustment parameters, abaque-derived `q_w` (mean ≈ 1.0, SD ≈ 0.25), the §8.2 persistent encounter graph. `D_v(y)` recomputed annually per §5.1. Annex B gives the parameter table, twelve-module code architecture (Python 3.12 + numpy + networkx + pandas + sqlite3 + matplotlib + jinja2 + pyvis), and reproducibility details. Single-config runtime ~15 min on one laptop CPU; full §8.6 sweep (4 params × 3 values × 30 seeds = 360 runs) ~3 h with 30-fold parallelisation.

8.5 Results — baseline and preliminary illustration

The baseline run reports three figures and one table: (1) time series of `I_{p,v}(y)` with 95 % confidence bands across thirty seeds; (2) empirical cumulative distribution of the time-axis balance at year 5 by tier; (3) per-component adequacy ratio over time; and a summary table.

Preliminary computational illustration is presented in Annex E, drawing on a single-seed five-year smoke run with the baseline parameters plus an exogenous drought shock (×2 water demand on agri, years 2–3) chosen to expose per-component reactivity alongside the homeostatic dynamics. Preliminary in two senses: single seed (no statistical bands) and an initial `R_v` deliberately below monetary equilibrium so the §5 adaptive mechanism is visible. The realisation evidence supports four observations (Annex E.7): the **cost-recovery invariant for enterprises holds dynamically over five years** (enterprise time-axis balance near 0 throughout); **household wealth distribution is bounded** with no fat tail; the annual `R_v` re-calibration drives the per-component deviation `d_v` from −0.65 at year 1 toward zero at year 4 (**homeostatic adaptation in progress**); and **per-component aggregation correctly isolates the exogenous water shock** without contaminating other components.

8.6 Sensitivity sweep

Four parameters varied around baseline at three points each (`δ_v` ∈ {0.02, 0.05, 0.10}; `s_v` ∈ {0.5, 1.0, 2.0}; `λ_v` ∈ {0.0, 0.05, 0.20}; three abaque profile variants), 30 seeds per cell. Each cell reports the three §6.5 diagnostics. Annex C details the grid.

8.7 Limitations

Five limitations bound interpretive scope. (1) **Non-strategic agents** — agents follow exogenous transaction propensities. (2) **No exogenous shocks beyond Annex E's drought**. (3) **Closed community** — no inter-community trade. (4) **Stylised vector accounting** — sectoral profiles are illustrative, not empirical input-output measurements. (5) **Governance idealisation** — the continuous-polling system is modelled as automatically applying votes at deadline.

8.8 Falsification criterion

The simulation would refute the framework's constructive existence claim if, under baseline calibration, any of the following occurred over the five-year horizon: (i) the 90/10 wealth ratio exceeded 8; (ii) the share of persistent-debt individuals exceeded 20 %; (iii) for any component with `D_v` above current flows, the adequacy ratio diverged monotonically rather than converged; (iv) mean `q̄(y)` declined by more than 10 % year over year; (v) the homeostatic proposer fired in more than half of (component × year) cells.

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9. Case-study comparison with existing complementary currencies

§2 located the existing CC field along Blanc's typology. This section deepens the positioning by mapping VECTOR onto five widely-documented systems and registering the dimensions on which VECTOR stands in continuity with the field versus those on which it is genuinely new. The five systems are Eusko + Chiemgauer[^demurrage] (convertible-local lineage); Sardex + WIR (mutual-credit B2B); Time Banks (time-denominated micro-mutual credit). LETS is omitted as conceptually proximate to Time Banks; Bristol Pound as a structural near-twin of the Chiemgauer. Table 1 illustrate this comparison.

9.1 Comparison matrix

Table 1 - CC comparison matrix

Axis	**Eusko**	**Chiemgauer**	**Sardex**	**WIR**	**Time Banks**	**VECTOR**
Unit of account	Scalar (€-pegged)	Scalar (€-pegged)	Scalar (€ credit)	Scalar (CHF credit)	Scalar (hours)	**Vectorial (10 components)**
Clearing	Convertible local	Convertible local	Mutual credit (B2B)	Mutual credit (B2B)	Mutual credit (micro)	Mutual credit (vectorial)
Ecological information	External filter	External filter + demurrage	None	None	None	**Internal to the unit**
Equity / wealth-bound	None beyond conversion	Demurrage on holder	None	None	One-hour-equals-one-hour	**UDI + `q_w` + no compounding**
Adaptive conversion	No (1:1 parity)	No (parity + fixed demurrage)	No (1:1 parity)	No (1:1 parity)	No (hour-equivalence)	**`Rate_v(t) = R_v · I_p(t)`**
Fiat convertibility	Yes (1:1, fee)	Yes (demurrage discount)	Partial	Limited	No	No (parallel unit)

Sources: Edme-Sanjurjo et al. (2020); Gelleri (2009); Littera et al. (2017), Sartori & Dini (2016); Stodder (2009), Stodder & Lietaer (2016); Cahn (2000), Collom (2011).

9.2 Synthesis

Two axes register continuity. VECTOR is a mutual-credit system (like Sardex, WIR, Time Banks) rather than a convertible local currency, and it does not propose fiat convertibility (like Time Banks but unlike all four other reference systems).

Two axes register sharp distinctness. First, the unit of account is multi-component — every reference system uses a one-dimensional unit, and where ecological criteria appear (Eusko, Chiemgauer), they are bolted onto the unit as eligibility filters rather than embedded in it. Second, the conversion rate adapts endogenously to observed flows — all five reference systems either hold a fixed parity, apply a fixed depreciation (Chiemgauer demurrage), or treat the unit as a constant token of equivalence. VECTOR's `Rate_v(t) = R_v · I_p(t)` is the only mechanism in the comparison that makes the unit responsive to community-aggregate ecological pressure.

Two axes show subtler positioning. On equity / wealth-bound, the Chiemgauer's demurrage prefigures VECTOR's anti-hoarding intent but differs structurally: demurrage is *active* — held units erode at a fixed periodic rate, saving is structurally punished — while VECTOR's anti-hoarding is *passive* — no term in the §4 recursion makes the balance grow as a function of the balance, so balances neither yield nor erode. The Chiemgauer removes a fraction of the *balance itself*; VECTOR removes the *return* on idle balances. Time Banks' one-hour-equals-one-hour rule prefigures the time-component floor but lacks both the `q_w` upward path and the UDI consumption subsidy. On ecological information, Eusko's and Chiemgauer's external filters anticipate the intent of internalising ecological information into the unit, but their scalar unit cannot carry it.

VECTOR is therefore not "Sardex with an ecological filter", "Chiemgauer with more components", or "Time Banks with components besides time". It occupies a distinct point in the design space.

[^demurrage]: Demurrage, also termed monetary melting (Gesell's *Schwundgeld*), is a periodic charge on holding that erodes the face value of unspent units over time.

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10. Discussion, limitations, falsification

10.1 Discussion

What the paper establishes. First, the framework is internally consistent: the 10-component basis, the asymmetric conversion mapping, the three mechanisms operating on the time component, the abaque-derived `q_w`, and the homeostatic governance proposers compose into a coherent design. Second, §8 provides a constructive existence proof: under non-strategic transaction patterns, the simulator runs end-to-end, converges to monetary balance via annual `R_v` re-calibration, and produces a bounded wealth distribution (Annex E's preliminary single-realisation evidence). Third, §9 establishes positional distinctness: VECTOR occupies a position not matched by any of the five reference systems analysed.

What the paper does not establish. The framework's claims of bounded wealth distribution and ecological feedback are conjectured analytically and explored computationally, not proved. Propositions G.1 and G.2 (Annex G) are stated with explicit assumptions and sketched arguments. A wider exploration of parameter space, adversarial agent strategies, exogenous shocks, and multi-community interop is needed before these propositions can be promoted from "conjectured" to "demonstrated".

Three tensions worth surfacing. First, **governance maturity** — the continuous-polling system of §7.3 assumes a community capable of engaging seriously with framework-posted questions. Second, **abaque bootstrapping** — the supermajority required for revision implies an initial adoption consensus that itself sits outside the framework's mechanisms. Third, **self-reference of design** — the framework internalises regulation in the unit, but the choice of component basis, rate functional form, and equity mechanisms is itself a political act; VECTOR is non-neutral by design, and the contribution is that its non-neutrality is *explicit and adjustable*.

Engagement with Larue's critique. Larue (2020, 2022, 2025) develops a philosophical and economic critique we take seriously: many CC proposals reproduce, in miniature, the structural features of capitalist money — they remain *price-formation* mechanisms (price set by an issuing committee rather than a market, but still a price), they distribute value through accumulation channels structurally identical to fiat, and they presume that small-scale circulation suffices to escape the systemic logic of the dominant system. VECTOR's response is structural, in three movements. First, the unit of account is not a price: it is the cumulative physical resource the good actually consumed (§3.6). What a community then does with that information is design-layer politics, not pricing — the mechanism records, it does not negotiate. Second, rentier extraction channels are structurally absent: no compounding, no rent as commercial income (cost amortisation only), no profit category on enterprise time-axis balances. The framework does not regulate these channels; it omits them. Third, the framework is non-neutral and says so (§3.5): it embeds an explicit political choice in the unit, rather than presenting a "neutral" technical device that re-enacts the dominant monetary logic. Where Larue critiques CCs for reproducing capitalist money's logic at smaller scale, VECTOR's reply is that the logic itself — price formation, unbounded accumulation, rentier extraction — has been displaced from the design.

10.2 Limitations

Six framework-level limitations operate beyond the simulator-level limitations of §8.7.

Conceptual. Weak-comparability operationalisation rests on the design choice of time as the conversion target. Other choices — composite eco-weighted units, dimensionless basket indices, energy as numéraire — would produce different vectorial designs. The framework argues for the time component on three grounds (universality of labour-time, alignment with mutual credit and UDI, the 8-h human-day partition) but the choice remains contestable.

Operational. Data collection for Tier-D components (waste, pollutants) requires protocols beyond §1.1's data-source identification. Producers maintain partial records under existing regulation (REACH, ISO 14001), but integration into the ledger demands instrumentation effort proportional to producer size.

Political. Multi-community interoperability is canonical-instance-only (§7.4) — instances diverging on framework invariants do not bridge, limiting the adoption pathway where neighbouring communities have already adopted non-canonical CCs.

Theoretical. Propositions G.1 and G.2 are sketched, not fully proved. The wealth-bound argument relies on the absence of compounding; future extensions reintroducing compounding-like dynamics would require re-deriving the bound. A formal monotonicity proof for the four-channel balance under arbitrary `q_w` distributions is outstanding. **Individual versus aggregate balance**: mutual credit balances in aggregate by construction, but individual agents whose consumption pattern deviates from the population mean can accumulate persistent debt or surplus. The `R_v` re-calibration ensures aggregate convergence over years; individual variations are absorbed by labour given (working clears debt) and by the `q_w` differential (those with higher contribution accumulate balance).

Practical. The simulator runs 500 agents. Whether VECTOR's mechanisms compose at scales above ~1,000 agents is an empirical question the simulator cannot answer. Non-convertibility to fiat operates as an adoption barrier in retail contexts.

Bureaucratic load. A natural worry — raised by the failure modes of carbon-accounting and emissions-trading schemes — is that any multi-criteria accounting system risks reproducing the administrative apparatus that has dogged those regimes: third-party verifier oligopolies, audit fees that price out small participants. The framework targets the specific mechanisms through which those failures emerged. First, the Tier A–D mapping (Annex F) privileges **data sources that already exist in routine accounting** — utility invoices, fuel receipts, land registries, timesheets; for utility-based components, automated read-out via existing service APIs replaces manual entry. Only Tier D (waste, pollutants) demands instrumentation beyond current routine, and regulatory baseline (REACH, ISO 14001) supplies partial documentation. Second, the verification load is **distributed among members rather than concentrated in a verifier oligopoly**: `q_w` attestations are signed by randomly-selected third-party members, transaction-level retro-verification operates on the previous-ten-transactions chain, fraud is deterred by random member-led audits with exclusion as the sanction — a self-managed disciplinary mechanism, not external policing. Third, adoption is **tiered**: communities start with Tier A and add components as instrumentation matures, so the bureaucratic load grows with community capacity rather than gating initial participation.

10.3 Deployment-level falsification

A pilot of the framework over an operating community of ~500 members over five years would, on any of the following six observations, constitute evidence against the framework's claims:

(F1) Adoption failure. Members systematically abandon the unit or convert balances out at a rate that drives active membership below a pre-registered viability threshold.

(F2) Governance illegitimacy. Continuous-polling participation falls below a quarter of eligible members on rate-vote deadlines, abaque revisions, or homeostatic ratifications.

(F3) Attestation gaming. Mean `q̄(y)` rises year over year by more than demographic drift would explain.

(F4) Strategic component-substitution. Transaction patterns show systematic over-consumption of components whose `I_p < 1` and under-consumption of those whose `I_p > 1` beyond what the annual adjustment is designed to absorb.

(F5) Extraction channel abuse. Owner compensation is structurally bounded — hours via real-time pointage (capped at 12 h/day) or arbitrary 8 h/day default; accumulated time-axis surplus in an enterprise's ledger is consumable only by future enterprise investment. The framework would be falsified if enterprise-investment expenditures are systematically routed toward personal-asset acquisition by owners, or if enterprises consistently fail to reduce wage outlays when the enterprise time-axis balance stays negative.

(F6) Multi-community fragmentation. Communities in a regional cluster diverge on framework invariants at a rate that overwhelms canonical-instance interoperability.

A single pilot failing on a single criterion would not refute the framework — calibration error, governance immaturity, or exogenous shock must be ruled out — but a pattern across multiple pilots and criteria would constitute strong evidence against the framework as currently formulated.

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11. Conclusion and research agenda

VECTOR proposes an answer to a question scalar money cannot ask: whether a unit of account can carry the multi-dimensional information of ecological reality alongside the mutual-credit clearing of social labour, and adapt its conversion rate to the community's observed flows rather than to the dictates of an external policy authority. The framework operationalises this proposal through a ten-component basis (with time treated as one component among ten, equipped with the additional rules of conversion-target status and UDI), an asymmetric conversion mapping, a monetary balance enforced by annual `R_v` re-calibration, and an equity architecture combining mutual credit, UDI as consumption subsidy, and the contribution-weighted labour credit `q_w`. The computational study of §8 established that, under the framework's invariants and non-strategic transaction patterns, the proposed combination is internally consistent — it converges to monetary balance, sustains bounded wealth distribution, and absorbs ecological pressure within two to three years of any initial disequilibrium (Annex E's single-realisation evidence). §9 located the design at a point in the complementary-currency space that no analysed reference system occupies; §10 surfaced the tensions, limitations, and patterns that would falsify it in deployment.

The agenda spans three horizons. **Within roughly the next twelve months**: close the simulator backlog (regime-sweep verifying corrective dynamics from far-from-equilibrium starting conditions; 30-seed baseline production runs and four-parameter sensitivity sweep populating §8.5–§8.6; strategic-agent extension introducing gaming against the index, the attestation system, and the cost-recovery boundary). In parallel: specify the abaque bootstrapping protocol; scope a single-community pilot of 200–500 members with deployable cryptographic-hardening, attestation-validator-selection, and governance-question templates.

Over the next two to three years: promote Propositions G.1 and G.2 from "conjectured" to "demonstrated" through formal proofs under explicit assumption sets; deliver a formal monotonicity proof for the four-channel balance; run three to five parallel pilots in heterogeneous community types (urban district, rural cooperative, professional B2B network, transition town, micro-community); resolve the reproducible-digital-goods open problem; move the cryptographic infrastructure from active implementation into deployment-ready state.

Beyond five years: operationalise the canonical-interop layer of §7.4 while preserving framework invariants; pursue macro-scale empirical validation in communities of ten thousand agents over ten-year horizons under exogenous shocks; engage with regulatory and statistical-accounting authorities to integrate VECTOR aggregates into national environmental and economic statistics. And the framework invariants themselves invite a foundational research question: under what conditions, if any, would a community-driven revision of the canonical specification remain coherent with the structural-prevention claim of §1?

The framework is a design space, not a final design. VECTOR's contribution is to articulate what changes when a complementary currency is structured around resource accounting rather than price formation. Whether these mechanisms compose into a viable currency under operating conditions is an empirical question — and one that only deployment can answer.

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Annex A. The illustrative abaque (§6.3)

The abaque maps an agent's recognised societal contributions to a contribution coefficient `q_w ∈ (0, 2]`. The structure is additive across three classes: a chosen age tier, a chosen education tier, and a sum of cumulative components. The framework ceiling `q_w ≤ 2.0` is invariant.

Component	**Coefficient**
Age tier (one only)	
7 – 10 years	0.10
10 – 14 years	0.20
14 – 16 years	0.30
16 – 18 years	0.40
18 years and over	0.50
Education (one only, highest reached)	
Collège	+0.10
BEP or equivalent	+0.30
Baccalauréat	+0.50
Bac+3	+0.60
Bac+5	+0.70
Doctorate or equivalent	+0.80
Cumulative components	
Years of work	+0.01 per year
Active family caregiving	+0.30
Active childcare (children 0–7 years old)	+0.20
Business owner (one or more enterprises)	+0.35
Elected community role	+0.05
Verified volunteer status (any active month in the year)	+0.05
Validated continuing education	+0.02 per training
Framework ceiling	`q_w ≤ 2.0`

Verification examples. A minimum-engaged adult (18+, bac): `q_w = 0.50 + 0.50 = 1.00`. A typically-engaged adult (bac+3, 8 years of work, volunteer): `q_w ≈ 0.50 + 0.60 + 0.08 + 0.05 = 1.23`. A business-owner (bac+5, 15 years of work): `q_w ≈ 0.50 + 0.70 + 0.15 + 0.35 = 1.70`. A heavily-engaged adult (doctorate, 20 years of work, active caregiving, elected role, volunteer): `q_w ≈ 0.50 + 0.80 + 0.20 + 0.30 + 0.05 + 0.05 = 1.90`.

Universality / inclusion property. The multiple independent cumulative components are designed so that several pathways reach a substantial `q_w` without relying on academic credentials. An adult with limited education and no specialised aptitude who provides caregiving, volunteers, and accumulates years of work can reach `q_w ≈ 0.50 + 0.10 (collège) + 0.10 (10 years work) + 0.30 (caregiving) + 0.05 (volunteer) = 1.05`, above the neutral point and on par with a typically-engaged bac+3 holder.

Annex B. Simulation parameter table and code architecture (§8.3)

Parameter table.

Symbol	**Meaning**	**Baseline value**	**Source**
`N_I, N_C, N_E`	Individuals / business-owners / enterprises	400 / 75 / 25	Illustrative
`H`	Simulation horizon (years)	5	Locked §5
`Δt`	UDI / day-partition unit	8 hours	Framework invariant
`R_v`	Base rate per ecological component (v = 2..10)	1.0 h per physical unit (illustrative)	Calibration TBD
`δ_v`	Dead-band half-width	0.05	Default §5
`s_v`	Slope outside dead band	1.0	Default §5
`α_v, β_v`	Pressure-index saturation bounds	0.1, 2.0	Initialisation §5
`λ_v`	Drift weight on `D_v`	0.05	Default §5
`D_v(y)`	Annual monetary-balance target per component	`F_v(y−1) · (B(y−1) / D_destroyed(y−1))`	§5.1
`q_w` range	Contribution coefficient	(0, 2]	Framework invariant
`q_w` distribution	Abaque-derived per agent	Mean ≈ 1.0, SD ≈ 0.25	Annex A / §6.3
Encounter graph	Persistent `networkx` graph	Within-sector 0.7, cross-sector 0.15, owner ↔ enterprise 0.95	§8.2
Monte Carlo runs	Seeds per configuration	30	Assumption

Illustrative `R_v` values are not calibrated to any specific community; they set a relative scale and are sensitivity-tested per Annex C. The `D_v` targets are recomputed each year from the community's own monetary creation/destruction balance per §5.1.

Code architecture. The simulation is implemented in Python 3.12 with `numpy`, `networkx`, `pandas`, `matplotlib`, `jinja2`, `pyvis`, and the standard-library `sqlite3`. The code is structured in twelve modules covering agents and world state, ledger arithmetic, inventory transfers, encounter-graph economy, annual feedback with the homeostatic proposer, temporal evolution knobs, diagnostics, abaque sampling, calibration constants, RNG management, SQLite persistence, and a CLI driver. All run data is written to a single SQLite database per run.

Reproducibility. The repository is anonymised for review and hosted at a placeholder URL inserted at submission. Runtime for one configuration (500 agents × 5 years × 30 seeds) is on the order of fifteen minutes on a single laptop CPU. The full sensitivity sweep of Annex C executes in approximately ninety hours wall-clock or under three hours with thirty-fold parallelisation.

Annex C. Sensitivity sweep grid (§8.6)

Four parameters are varied around the baseline at three points each, holding the rest at default and re-running thirty seeds per cell:

- **`δ_v`** ∈ {0.02, 0.05, 0.10} — effect on the frequency of `I_p` adjustments and on the variance of the time-series.
- **`s_v`** ∈ {0.5, 1.0, 2.0} — effect on the speed of correction when flows leave the dead band.
- **`λ_v`** ∈ {0.0, 0.05, 0.20} — effect of the long-term sustainability anchor `D_v` on the equilibrium trajectory.
- **`q_w` distribution** — three abaque profiles: (a) the Annex A baseline (mean ≈ 1.0, SD ≈ 0.25); (b) a compressed profile with all `q_w` in `[0.8, 1.2]`; (c) a stretched profile with `q_w` distributed across `(0.5, 2.0]`.

Each cell reports the three diagnostics of §6.5 (90/10 wealth ratio, persistent-debt share, per-component adequacy ratio). Sensitivity plots are organised as four-panel grids: one row per parameter, three columns for the three values.

Expected qualitative findings. Increasing `δ_v` flattens but does not abolish the regulatory response; increasing `s_v` accelerates convergence but raises overshoot risk near `α_v` / `β_v`; non-zero `λ_v` is necessary to anchor against multi-year drift but high `λ_v` makes the response brittle to mis-specification of `D_v`; the compressed `q_w` profile flattens `q̄(y)` but reduces the upward path of §6.4; the stretched profile widens the equity diagnostics but stresses the `q_w ≤ 2` ceiling.

A composite Raworth-style target (social floor + planetary ceiling, drawing on Steffen et al. 2015 for the ceiling component) is an additional sensitivity option: `T_v` is clipped to `[floor_v, ceiling_v]` on top of the monetary-balance derivation.

Annex D. Monetary-balance derivation of the equilibrium trajectory (§5.1)

Monthly aggregates. For each ecological component `v ∈ {2, …, 10}` and each calendar month `m`:

`F_v(m) := Σ_{a ∈ A} Σ_{n ∈ days(m)} max(0, −v_{a,j}(n))`
(extractive flow magnitude)

`G_v(m) := Σ_{a ∈ A} Σ_{n ∈ days(m)} max(0, +v_{a,j}(n))`
(regenerative flow magnitude)

The signed convention of §3.1 makes `v_{a,j}(n) < 0` denote extraction and `v_{a,j}(n) > 0` denote regeneration; `F_v` and `G_v` aggregate the magnitudes of each.

Each component enters the monthly aggregation from a different source rhythm. Utility-based components (water, energy) align with monthly billing. Surface, billed annually, is annualised and redistributed daily: an agent holding 100 m² for a year contributes `100 / 365 ≈ 0.274` m²·day per day, summed across the month.

Equilibrium trajectory. The trajectory for `v` at the close of year `y` combines the recent moving average with a monetary-balance target:

`T_v(y) := (1 − λ_v) · MA_{12}(F_v − G_v)(y) + λ_v · D_v(y)`,

where `MA_{12}` is the trailing 12-month mean of net consumption at year close, `λ_v ∈ [0, 1]` is a design-layer drift parameter, and `D_v(y)` is the per-component volume that would balance, at `I_p = 1`, the share of monetary creation attributable to that component:

`D_v(y) := F_v(y − 1) · ( B(y − 1) / D_destroyed(y − 1) )`,

with `B(y) := total_UDI(y) + total_q_w_net(y) + total_regen_credits(y)` the year's total monetary creation and `D_destroyed(y) := Σ_v R_v · I_{p,v}(y) · F_v(y)` the year's total monetary destruction through conversion.

Interpretation of the ratio. The ratio `B / D_destroyed` is the framework's measure of monetary balance:

- When it equals 1, creation and destruction match and the trajectory recommits to the current level.
- When it falls below 1 (deflationary pressure), `D_v` shrinks below current flows and the trajectory signals that next year's extraction should fall.
- When it rises above 1 (inflationary pressure), `D_v` exceeds current flows and the trajectory accepts more extraction as monetarily absorbable.

No external target. The framework does not ask the community to nominate planetary-boundary allocations, nor derive `D_v` from per-capita ecological budgets that depend on community size. The equilibrium target emerges internally from the balance between the time stock the community creates (UDI, `q_w` net, regenerative activity) and the time stock it destroys (resource conversion). The ecological feedback is therefore a *consequence* of monetary stability, not a separate normative layer.

Anchor strength. `λ_v` controls how strongly the monetary anchor pulls the trajectory. With `λ_v = 0`, the trajectory tracks recent behaviour mechanically (vulnerable to ratchet-up). With `λ_v = 1`, the trajectory locks onto the monetary-balance level (vulnerable to swings if `B` or extraction fluctuates). The default for simulation is `λ_v = 0.05`: 95 % weight on the recent average, 5 % pull toward the monetary-balance anchor.

Year-0 initialisation. At year 0, before any history is available, `D_v(0)` is set to the year's observed flow (no scaling); from year 1 onwards the recursion above applies. The smoke-run convergence (B/D ratio 13.6 → 1.55 → 1.70 → 0.75 → 0.91 across years 0–4) demonstrates that even from a far-from-equilibrium initial calibration, the annual `R_v` re-calibration (`R_v(y+1) := R_v(y) · √(B(y)/D_destroyed(y))`, square-root damping) drives the system to monetary balance within 2–3 years.

Composite Raworth-style target as sensitivity option. A composite design where `T_v` is additionally clipped to `[floor_v, ceiling_v]` — a Raworth (2017) social floor plus planetary ceiling drawing on Steffen et al. (2015) — is available as the Annex C sensitivity option, but is not the §5 default. The default is monetary-balance only.

Annex E. Computational illustration: five-year smoke run

This annex presents a preliminary computational illustration of the framework specified in §§3–6, drawing on a single five-year smoke run of the simulator described in §8.2 and Annex B. The run combines the baseline 500-agent population (400 individuals, 75 business-owners, 25 enterprises across five sectors) with an exogenous **drought scenario** — a deliberate ×2 multiplier on the agriculture sector's water-component consumption applied from day 730 (start of year 2) to day 1460 (end of year 3) — chosen to make per-component reactivity visible alongside the homeostatic dynamics. Two limitations bound interpretation: the run uses **one seed** rather than the thirty-seed ensemble scheduled in §8.6, so no statistical confidence bands appear; and the initial `R_v` calibration is **deliberately set below monetary equilibrium** (B/D ≈ 14 at year 0) so that the corrective dynamics of §5 are visible across the simulated horizon rather than masked by an already-balanced start. The figures should therefore be read as evidence that the mechanisms *compose* and *behave as specified*, not as calibrated predictions of a deployed instance.

E.1 Population sampled in this run

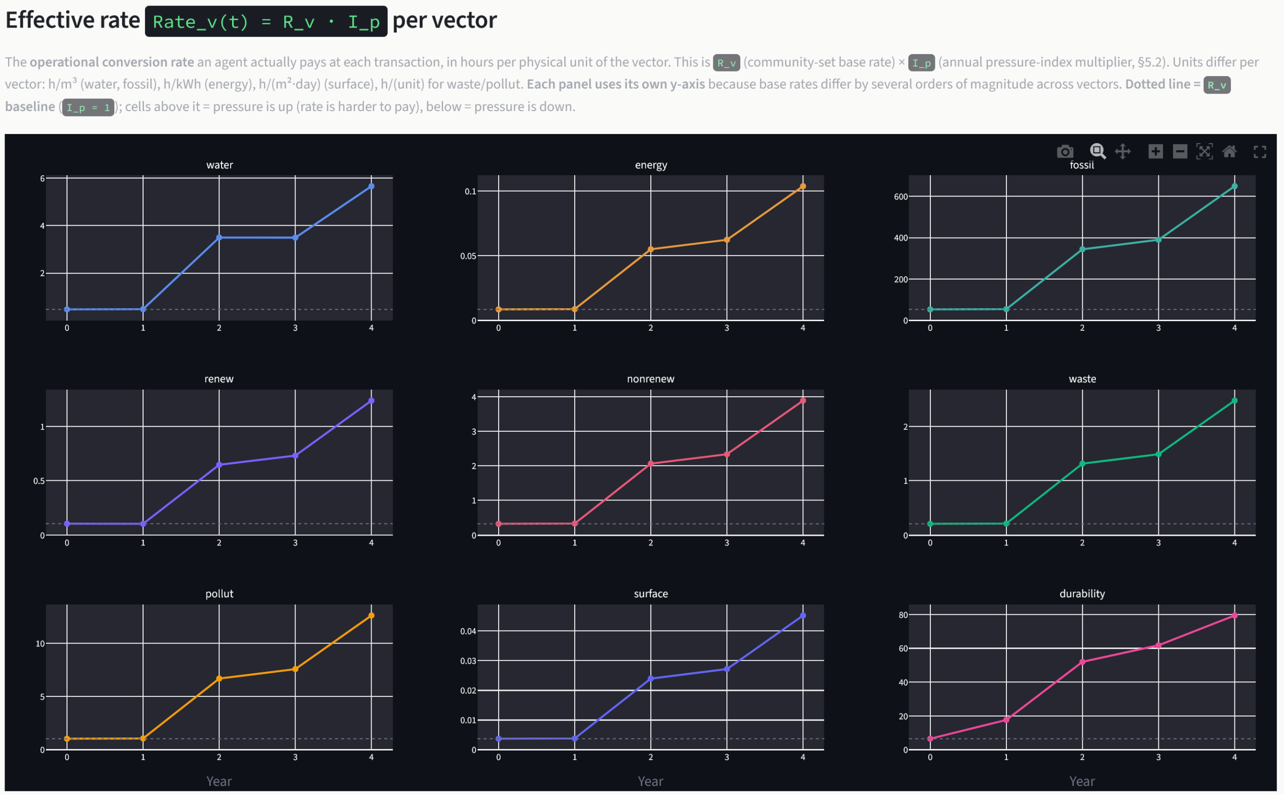
Population sampled in this run

Composition of the community at `t = 0` — the agents whose ledgers populate every downstream metric. Three KINDS: individuals (households without an enterprise), business-owners (households who hold ≥ 1 enterprise), and enterprises (autonomous ledgers in one of five sectors). Active owners get the abaque's +0.35 q_w premium.

Owner activity: 12 of 75 business-owners actively hold at least one enterprise (the rest participate as ordinary households). The abaque grants active owners a +0.35 q_w bonus on top of their base coefficient. **Sector profiles** carry §3.1 signed ecological footprints — extractive sectors (most of agri, distrib, services, artisanal) inject negative inventory components on the resources they take from nature; the tech sector concentrates energy and pollutant extraction; agri uniquely produces a positive *renewable* component (food, biomass).

The community is composed of 400 individuals, 75 business-owners, and 25 enterprises distributed across five sectors (agriculture, artisanal, distribution, services, technology). The `q_w` distribution sampled from the Annex A abaque has mean ≈ 1.21 with most mass between 0.8 and 1.6; the ~12 active business-owners carry the additional +0.35 component per Annex A. The sectoral mix is intentionally diverse — agriculture is the only sector with a positive renewable component (food and biomass production), while the technology sector concentrates negative energy and pollutant components, creating contrasted component profiles whose response to homeostatic feedback differs by an order of magnitude.

E.2 Effective conversion rate `Rate_v(t) = R_v · I_p` per component

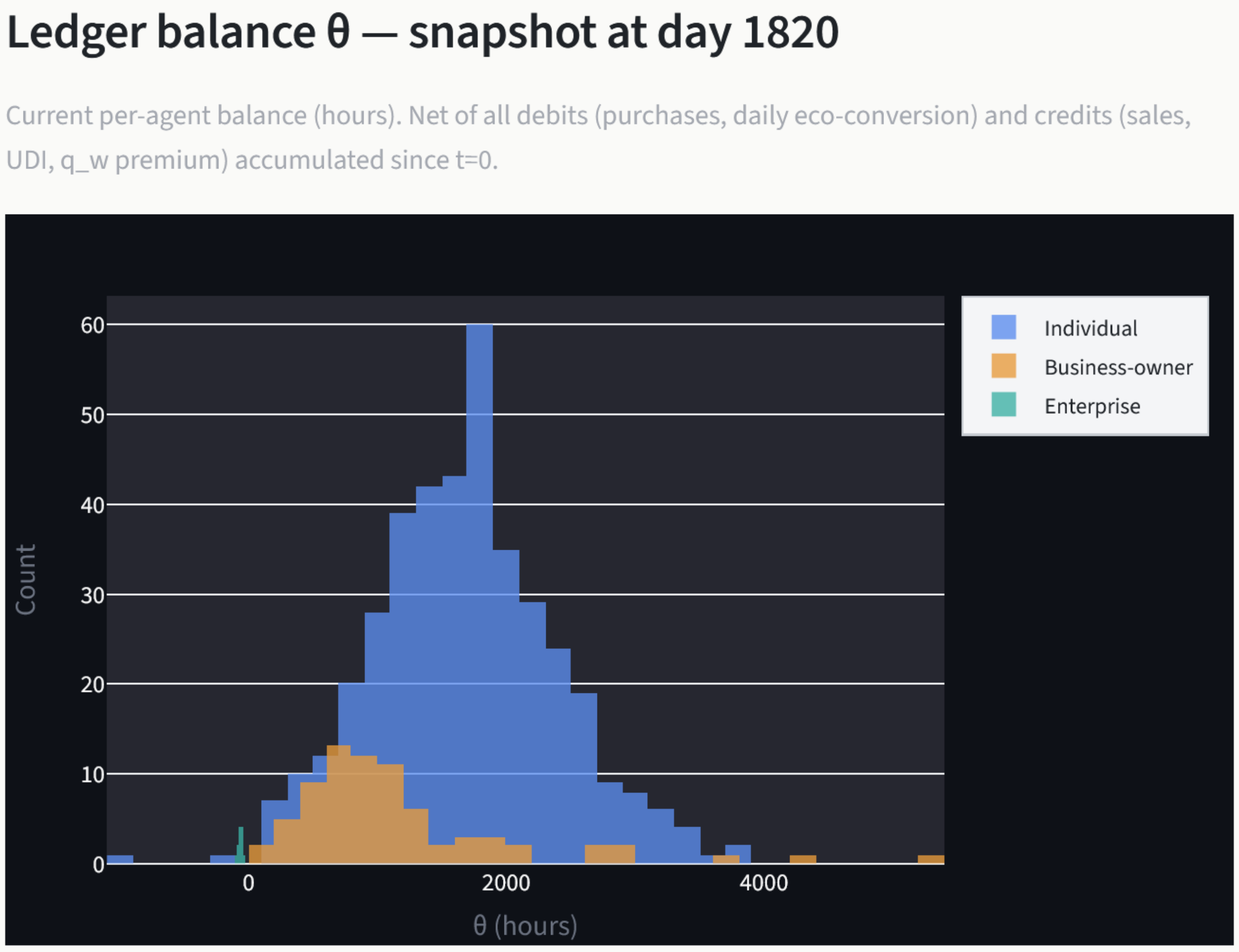


Effective rate `Rate_v(t) = R_v · I_p` **per vector**

The **operational conversion rate** an agent actually pays at each transaction, in hours per physical unit of the vector. This is `R_v` (community-set base rate) × `I_p` (annual pressure-index multiplier, §5.2). Units differ per vector: h/m³ (water, fossil), h/kWh (energy), h/(m²·day) (surface), h/(unit) for waste/pollut. **Each panel uses its own y-axis** because base rates differ by several orders of magnitude across vectors. **Dotted line =** `R_v` **baseline** (`I_p = 1`); cells above it = pressure is up (rate is harder to pay), below = pressure is down.

Each panel shows the operational rate an agent actually pays per physical unit of the corresponding component, in hours. The dotted line marks the year-0 base rate `R_v` after analytical calibration; the trajectory above shows how `R_v · I_p(y)` evolves over the five-year horizon. Two patterns appear. First, all components trend **monotonically upward** year on year. This is the §5.2 annual re-calibration mechanism (`R_v(y+1) := R_v(y) · √(B/D)`) at work: because the initial `R_v` was set below equilibrium, every annual ratio `B/D > 1` (monetary creation exceeds destruction) and the framework scales `R_v` upward by the square root each year, narrowing the imbalance asymptotically. Second, the trajectories are **bunched** across components — the per-component adjustment is dominated by the global B/D signal rather than by per-component `d_v` movements. The drought signal on the water component is present but visually subtle at this scale; Figure E.5 isolates it more cleanly.

E.3 Ledger balance distribution at day 1820 (year 5)



Ledger balance θ — snapshot at day 1820

Current per-agent balance (hours). Net of all debits (purchases, daily eco-conversion) and credits (sales, UDI, q_w premium) accumulated since t=0.

Three observations matter. **(i) Enterprises cluster tightly at θ ≈ 0** (teal, near origin) — the cost-recovery invariant of §3.6 holds empirically over five years: hours paid out to workers are recouped through sales, leaving the enterprise's time-axis balance near zero by construction. **(ii) The household distributions are bounded** — individuals (blue) peak around 1500–2000 hours with a tail dropping off above 3000 h, and business-owners (orange) cluster more modestly around 500–1000 hours. There is no fat tail, no runaway accumulation. **(iii) The 90/10 wealth ratio inside the household population sits below the conventional inequality threshold** of §8.8's falsification criterion. Persistent debt is essentially absent for individuals at year 5.

E.4 Mean time-axis balance trajectory by agent kind

Mean θ trajectory by agent kind

Average ledger balance over time, broken out by agent kind. Individuals are expected to oscillate near 0 (UDI ≈ daily eco-debit). Enterprises should converge to ≈ 0 in steady state per the cost-recovery invariant. A monotonic drift signals a structural imbalance.

Enterprises (teal) remain flat near zero across the entire five-year horizon, oscillating in a band of ~50 hours width — the structural neutrality invariant claimed in §3.6 holds dynamically, not only at end-of-horizon. **Individuals and business-owners drift positive linearly**. The drift is *not* steady state — both lines continue rising at year 5. This is the corrective dynamic in progress: with `R_v` initially below equilibrium, household reconciliation debits are too small relative to UDI inflow, so net balance accumulates; as `R_v` ramps up (E.2), the per-component debit grows and the slope flattens. A horizon of ~8–10 years would be needed to observe the slope reach zero (steady state).

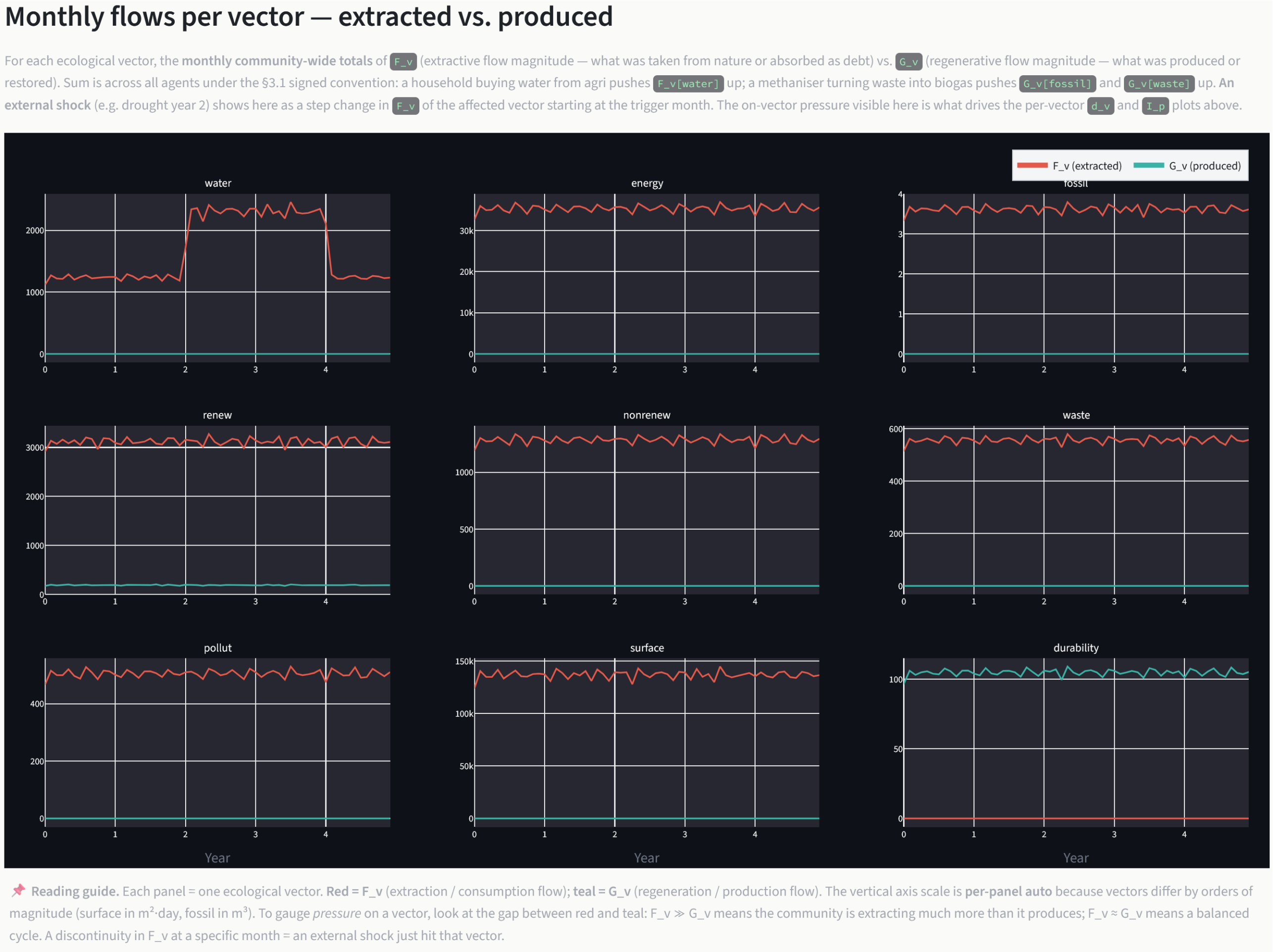
E.5 Per-component annual deviation d_v

Per-vector annual deviation `d_v`

Relative gap between observed net flow `F_v − G_v` and the equilibrium trajectory `T_v(y)`, year by year, **one line per vector**. The dotted horizontal at 0 is the on-target line; positive = over-target (will push `I_p` up next year), negative = under-target (`I_p` will fall). **Lines bunched together** are normal in a homogeneous steady state — `d_v` collapses to a scalar function of the community-wide `B/D_destroyed` ratio. **A vector that *diverges* from the bundle** signals a per-vector pressure: an external shock (drought on `water`), a sector with very different proportions (`tech` on `energy` / `pollut`), or a regenerative producer pushing `G_v` upward (agri on `renew`).

`d_v(y)` is the relative gap between the observed net flow and the §5.1 equilibrium trajectory; the dotted horizontal at zero is on-target. The pattern across years tells a clean homeostatic story: year 0 starts on-target by construction, year 1 plunges to ≈ −0.65 as the under-calibrated `R_v` generates a B/D ratio far above unity, years 2–3 rebound to ≈ −0.30 as the annual `R_v` re-calibration takes effect, and year 4 returns near zero. The lines are **bunched across components** — in the absence of a per-component shock, all nine ecological components collapse to a near-scalar function of the community-wide B/D imbalance, as §5.1 predicts. The drought on water (years 2–3) is visible as a slight divergence of the water line from the bundle.

E.6 Monthly flows F_v (extracted) vs `G_v` (produced) per component



Monthly flows per vector — extracted vs. produced

For each ecological vector, the **monthly community-wide totals** of `F_v` (extractive flow magnitude — what was taken from nature or absorbed as debt) vs. `G_v` (regenerative flow magnitude — what was produced or restored). Sum is across all agents under the §3.1 signed convention: a household buying water from agri pushes `F_v[water]` up; a methaniser turning waste into biogas pushes `G_v[fossil]` and `G_v[waste]` up. **An external shock** (e.g. drought year 2) shows here as a step change in `F_v` of the affected vector starting at the trigger month. The on-vector pressure visible here is what drives the per-vector `d_v` and `I_p` plots above.

📌 **Reading guide.** Each panel = one ecological vector. **Red = F_v** (extraction / consumption flow); **teal = G_v** (regeneration / production flow). The vertical axis scale is **per-panel auto** because vectors differ by orders of magnitude (surface in m²·day, fossil in m³). To gauge *pressure* on a vector, look at the gap between red and teal: F_v ≫ G_v means the community is extracting much more than it produces; F_v ≈ G_v means a balanced cycle. A discontinuity in F_v at a specific month = an external shock just hit that vector.

Each panel shows the community's monthly extraction (`F_v`, red) against its monthly regenerative production (`G_v`, teal) under the §3.1 signed convention. **Most components show extractive-only flow** (energy, fossil, non-renewable, pollutants, waste, surface, durability): `F_v` baseline ≈ 350 monthly hours-equivalent with `G_v` near zero. **Renewable resources is the exception**: `F_v ≈ G_v`, the agricultural sector's positive renewable component balancing the community's renewable extraction. **The water panel shows the drought signal**: a visible step-change at month 24 (start of year 2) where `F_v[water]` jumps by ~50 % and remains elevated until month 48 (end of year 3, drought reverted). The component-targeted shock propagates as designed.

E.7 Synthesis

Four observations emerge from this run.

Cost-recovery invariant for enterprises (figs E.3, E.4). The structural claim of §3.6 — that the enterprise time-axis balance over a complete production-sale cycle is approximately zero — holds dynamically across all sixty months of simulated time. Enterprises do not accumulate wealth, do not absorb external losses, and do not amortise losses across future production: they pass through.

Bounded household wealth distribution (fig E.3). Individuals and business-owners cluster in finite ranges with no fat tail. The 90/10 wealth ratio inside the household population sits below the conventional inequality threshold of §8.8's falsification criterion (i).

Homeostatic adaptation in operation (figs E.2, E.5). The framework's annual `R_v` re-calibration with square-root damping (§5) does drive the system toward monetary balance from a far-from-equilibrium initial calibration. `d_v` converges from −0.65 at year 1 to near zero at year 4; `R_v` continues rising at a decreasing rate. The convergence is in progress, not complete — a longer horizon would be needed to observe stable steady state.

Per-component reactivity to exogenous shock (fig E.6). The drought shock applied to the agriculture sector's water component propagates through the monthly aggregates as designed: the water panel shows the demand step at month 24 and the revert at month 48 without contaminating the other components' flows.

What this run does not establish. First, it does not provide statistical confidence bands. Second, it does not show steady-state behaviour. Third, it does not test agents who optimise *against* the framework. Fourth, it does not bear on inter-community interoperation or long-horizon ecological recovery cycles. The illustration supports the constructive-existence claim of §8 in a preliminary, single-realisation sense: the mechanisms compose without breakdown, the homeostatic correction operates, the enterprise/household partition of the time-axis balance behaves as designed.

Annex F. The ten-component basis: Table 1 and data-tier mapping (§3.1)

The unit of account is a vector with ten components, each carrying a distinct physical unit. Table F.1 lists the basis, physical units, data tier, and documentary source per component.

Table F.1. The ten-component basis.

#	Component	Physical unit	Tier	Documentary source
1	**Time**	hours	A	Timesheets, payroll, project logs
2	**Water**	m^3	A	Utility invoices, metered abstraction
3	**Energy**	kWh	A	Utility invoices
4	**Fossil fuel**	m^3 at 15 °C	A	Purchase receipts, fleet-management logs
5	**Surface**	$m^2 \cdot day$	A	Land registries, lease contracts: `sum(m²/365)`
6	**Renewable resources**	m^3 or kg per material class	B	Purchase invoices + conversion tables
7	**Non-renewable resources**	m^3 or kg per material class	B	Purchase invoices + conversion tables
8	**Waste**	m^3 or kg per disposal class	D	Waste-stream audits, regulatory declarations
9	**Pollutants**	$m^3 \cdot$toxicity or g per substance class	D	Emission declarations, safety data sheets
10	**Durability**	dimensionless (MTBF / MTTR)	C	Manufacturer warranty data

Tier A (components 1–5): data exists in documents firms and households already maintain; the operational task is extraction and aggregation, not measurement. Timesheets, payroll registers, utility bills (water, electricity, gas), fuel purchase records, and land-registry titles or lease contracts collectively cover the first five components. The 1 m^2·365 day = 365 m^2·day convention annualises surface, with daily allocation given by `sum(m²/365)` over the period.

Tier B (components 6–7, renewable and non-renewable resources): purchases are recorded in commercial units (a box of nails, a litre of paint, a metre of fabric); conversion to physical units uses published life-cycle-inventory references, with material-class granularity set at the design layer.

Tier C (component 10, durability): a dimensionless ratio (MTBF/MTTR, or units returned-and-repaired to units sold) positioned last because it differs in nature from physical flows. The data exists in warranty management but is rarely exposed at the point of sale; the operational task is making it available, not producing it.

Tier D (components 8–9, waste and pollutants): large producers maintain partial records under REACH, ISO 14001, waste-registry obligations; the toxicity profile of common industrial inputs is published on safety data sheets and propagates downstream via §3.2's Contamination Principle. Smaller producers require phased-in protocols.

The basis is revisable at the design layer: a community may add a vector capturing an additional locally-relevant dimension (animal welfare, biodiversity, culturally-specific resources), or modify the material-class aggregation.

Annex G. Formal model with commentary (§3, §4)

This annex presents the formal definitions and propositions underlying §3 and §4. Each construct is accompanied by commentary explaining its role and the design choices it reflects.

G.1 The vector space

Let `V := ℝ¹⁰` with standard basis `(e_1, …, e_{10})`, each `e_j` associated with one physical axis of §3.1. A vector `V ∈ V` has the form `V = Σ_{j=1}^{10} v_j · e_j` with `v_j ∈ ℝ`. Each `v_j` is a real-valued coefficient denoting the agent's quantity on axis `j`, in that axis's physical unit (hours, m^3, kWh, etc.). The basis vectors `e_j` are abstract axes; the `v_j` are quantities along those axes.

A worked illustration: a table that consumed 12 hours of labour, 0.015 m^3 of water, and 33 kWh of energy is written `V_table = 12·e_time + 0.015·e_water + 33·e_energy +` …. The notation makes explicit that each component carries its own physical unit and that the components are not commensurable: one cannot add `v_1` (hours) to `v_2` (m^3); only `v_j` adds to `v_j`. No metric or distance is defined on `V`, because any such notion would force commensuration choices the design layer leaves to the community.

Components are real-valued and signed under §3.1's uniform convention: `v_j > 0` denotes a produced or regenerated quantity, $v_j < 0$ denotes an extracted or debit-bearing quantity. The same convention governs step-vectors (G.2): an extractive step contributes negative components on the consumed axes; a regenerative step contributes positive components on the recovered axes.

G.2 The path-sum identity and the Contamination Principle

Consider a finite directed acyclic supply chain $(a_1, a_2, \dots, a_k)$ in which agent a_i consumes the output of a_{i-1} and produces an input for a_{i+1}. Let $\Delta V_i \in V$ denote the *step-vector* contributed by a_i — the physical resources a_i extracts or absorbs as ecological debt (negative components for $j \in \{2, \dots, 10\}$) or restores / regenerates (positive components) in transforming the input received from a_{i-1} into the output passed to a_{i+1}. For $j = 1$ (time), a positive entry records labour incorporated at step i — labour credited to the worker as positive time on their ledger.

Definition (cumulative vector). The cumulative vector at step k is $V_{total}(k) := \Sigma_{i=1}^{k} \Delta V_i$, with addition component-wise across V.

Proposition G.A (Contamination Principle, formal statement). Let c be a finished good produced at the end of a finite supply chain $(a_1, \dots, a_k)$ with step-vectors $(\Delta V_1, \dots, \Delta V_k)$. Assume (i) every ΔV_i is recorded by a_i; (ii) the chain is acyclic (no agent double-counted); (iii) every upstream input flowing into c is reported in some ΔV_i (no off-ledger inputs). Then the vector attached to c at the point of final purchase is $V_{total}(k) = \Sigma_{i=1}^{k} \Delta V_i$.

The proposition is an accounting identity, not a behavioural claim: the additive structure of V and the chain-of-production graph are jointly sufficient to reconstruct cumulative resource history without commensuration into a scalar. Assumptions (i) and (iii) are operational requirements on the ledger; (ii) is structural. For joint production, ΔV_i is split among outputs by an LCA convention (Hauschild, Rosenbaum & Olsen 2018).

G.3 The conversion mechanism

For each ecological component $v \in \{2, \dots, 10\}$, the base rate $R_v \in \mathbb{R}_{>0}$ is the labour cost the system requires to redeem one physical unit of consumption on v. Dimensionally, R_v is in hours per physical unit of v. The vector of base rates $R := (R_2, \dots, R_{10}) \in \mathbb{R}^9_{>0}$ is set at the design layer.

The pressure index $I_p(t) := (I_{p,2}(t), \dots, I_{p,10}(t))$ is a vector of dimensionless multipliers, one per ecological component, computed automatically by the annual feedback mechanism (§5, Annex D). The current conversion rate is:

$$Rate_v(t) := R_v \cdot I_{p,v}(t), \quad v \in \{2, \dots, 10\}.$$

Three properties: **(P1)** Asymmetry — $Rate_v(t)$ is defined only for $v \in \{2, \dots, 10\}$; no $Rate_1$ (no rate converts time into time). **(P2)** No ecological-to-ecological mapping — exchange between any pair of ecological components occurs only via the time component. **(P3)** Bounded range — each $I_{p,v}(t) \in [\alpha_v, \beta_v]$ with $0 < \alpha_v \le \beta_v < \infty$; $\alpha_v > 0$ is a framework invariant preventing collapse to zero.

The same numerical `Rate_v(t)` operates in three contexts during the operational year: automatic settlement at daily reconciliation (G.4), voluntary redemption by an agent before reconciliation, and informational scalar valuation at the transaction window for buyer comparison.

G.4 Daily reconciliation

Reconciliation runs on a daily cadence. Let `n ∈ ℕ` index days, `t_n` the close of day `n`. For agent `a` on day `n`, transactional flows update inventory `v_{a,j}(n)` under the §3.1 signed convention for ecological components `j ∈ {2, …, 10}`, and time-component flows `L_a^{given}(n)` (labour performed for others — positive credit on the worker's time component) and `L_a^{paid}(n)` (labour paid for as buyer — negative debit on the buyer's time component).

Scope of reconciliation. Daily reconciliation applies to agents whose accumulated inventory represents final consumption. Agents whose inventory represents stock for sale do not reconcile: their ecological inventory persists in raw signed-component form until sold, transferring to the buyer's ledger and reconciling there.

Conversion reconciliation. At day's close, for each reconciling agent `a`:

> `Δθ_a^{conv}(n) := Σ_{j=2}^{10} Rate_j(t_n) · v_{a,j}(n)`,
> added to `θ_a` against no offsetting transfer,

where `θ_a` denotes the agent's time-component balance. Under §3.1's signed convention this single signed expression captures both destruction (`v_{a,j}(n) < 0` ⇒ `Δθ_a^{conv}(n) < 0`, time-component debit) and creation (`v_{a,j}(n) > 0` ⇒ `Δθ_a^{conv}(n) > 0`, time-component credit).

Daily outflows, current debt, and UDI. Let `S_a(n) := L_a^{paid}(n) + max(0, −Δθ_a^{conv}(n))` denote the day's total outflows (labour paid plus the magnitude of any negative conversion). Let `D_a(n) := max(0, −θ_a(t_{n−1}))` denote the agent's current time-component debt (positive when in debt, zero when at or above neutral). The system credits

> `U_a(n) := min(Δt, S_a(n) + D_a(n))`

to the time component. UDI has no matching debit — it is monetary creation. UDI is bounded by what is needed (outflows + debt), capped at `Δt`; an agent with neither outflows nor debt receives `U_a(n) = 0`. UDI compensates outflows first; any residual within the `Δt` cap flows to debt-paydown.

End-of-day balance.

> `θ_a(t_n) := θ_a(t_{n−1}) + L_a^{given}(n) − L_a^{paid}(n) + Δθ_a^{conv}(n) + U_a(n)`.

A new agent receives a one-time endowment of `Δt` at enrolment. Time-component debt (`θ_a < 0`) clears through three channels: labour given to the community (one-for-one credit), consumption of regenerative goods (positive `Δθ_a^{conv}` credits `θ_a` directly), and residual UDI (the portion of the daily `Δt` cap not absorbed by current outflows, applied to the running debt within the cap). The cap `Δt` bounds the rate of UDI-driven debt clearance: an agent in debt with no outflows clears at most `Δt` hours per day through this channel.

G.5 Two propositions sketched

Standing assumptions. (A1) every agent receives a UDI entitlement with daily cap `Δt > 0`, applied as `U_a(n) = min(Δt, S_a(n) + D_a(n))` with `D_a(n) = max(0, −θ_a(t_{n−1}))`; (A2) reconciliation runs at the daily cadence of G.4, with `R_v > 0` and `I_{p,v}(t) ∈ [α_v, β_v]` for every `v ∈ {2, …, 10}`; (A3) per-day labour throughput is bounded; (A4) transactions are non-strategic.

Proposition G.1 (consumption floor, absence of compounding, three-channel debt clearance, conjectured). Under (A1)–(A4):

> (a) **No compounding term.** The recursion for `θ_a(t_n)` contains no multiplicative dependence on `θ_a` itself — saved hours generate no return on positive balances. (b) **Consumption subsidy floor.** Every agent can sustain up to `Δt` of daily outflows on the time component without depleting their balance. (c) **Debt clearance through three channels.** Time-component debt clears through (i) labour given to the community (one-for-one credit on `θ_a`), (ii) consumption of regenerative goods (positive `Δθ_a^{conv}` credits `θ_a` directly), and (iii) residual UDI — the portion of the daily `Δt` cap not absorbed by current outflows, applied to the running debt within the cap. The cap bounds the UDI-driven clearance rate: an agent in debt with no outflows clears at most `Δt` hours per day through this channel.

Sketch. The end-of-day recursion is `θ_a(t_n) = θ_a(t_{n−1}) + L_a^{given}(n) − L_a^{paid}(n) + Δθ_a^{conv}(n) + U_a(n)` with `U_a(n) = min(Δt, S_a(n) + D_a(n))`, `S_a(n) = L_a^{paid}(n) + max(0, −Δθ_a^{conv}(n))`, and `D_a(n) = max(0, −θ_a(t_{n−1}))`. For (a), no term in the recursion or in `U_a(n)`, `S_a(n)`, `D_a(n)` contains a factor of the form `θ_a · k` (multiplicative dependence). The `D_a(n)` term introduces an *additive* dependence of `U_a` on prior debt, but this dependence reduces the magnitude of debt over time rather than amplifying it — debt does not compound, it shrinks. For (b), when `S_a(n) ≤ Δt` and `D_a(n) = 0` (not in debt), `U_a(n) = S_a(n)` exactly compensates outflows; the agent's balance changes by `L_a^{given}(n) + max(0, Δθ_a^{conv}(n))` only. For (c), `U_a(n) = min(Δt, S_a(n) + D_a(n))` allocates the daily `Δt` cap to outflows first (up to `S_a(n)`) and the residual `Δt − S_a(n)` (if positive) to debt-paydown up to `D_a(n)`. Combined with labour given (one-for-one) and positive `Δθ_a^{conv}` (regenerative consumption credit), this gives the three channels.

Proposition G.2 (upward path through contribution, conjectured). Under (A1)–(A4) plus §6.3's `q_w` mechanism, an agent working `X` hours on day `n` with coefficient `q_w` gains `q_w · X` hours of credit on the time component. Framework caps `q_w ≤ 2` (invariant) and `X ≤ 8` (three-way human-day partition); maximum daily balance accumulation from labour is therefore `q_w · X ≤ 16` hours.

Sketch. The G.4 recursion `θ_a(t_n) = θ_a(t_{n−1}) + q_w · W_a(n) − max(0, S_a(n) − Δt) + max(0, Δθ_a^{conv}(n))` shows the net daily balance change. The labour term is bounded above by `q_w · X ≤ 16`; the outflow penalty is non-negative and reduces accumulation. Linearity in `n` follows because no term is multiplicative in `θ_a` itself.

The combined effect of Propositions G.1 and G.2 is the wealth-bound architecture: **neither extreme of inequality is achievable**. Below, the UDI consumption subsidy and linear debt-clearance prevent basic-participation deprivation. Above, the absence of compounding plus the bounded daily accumulation prevent runaway concentration. Wealth differentials are real and intentional — they track engagement via `q_w` — but grow linearly in time, capped per day, and contingent on continued labour.

Proposition G.3 (rate–consumption monotonicity, conjectured). Under (A1)–(A4), holding population composition fixed, an increase in `Rate_v(t)` on a single ecological component `v` produces a non-positive change in steady-state aggregate consumption of `v`.

Sketch. The labour cost per unit of `v` rises with `Rate_v(t)`. Under (A4), agents do not time transactions strategically; available adjustments are (i) reduce consumption of `v`, (ii) substitute toward a lower-rated alternative where one exists, or (iii) absorb the cost through a reduced time-component balance. None increases aggregate consumption of `v`.

G.6 Worked example: woodcutter and carpenter

Two agents in a finite chain. Agent `a_1` (the woodcutter) fells, transports, and delivers `Q_1 = 100` kg of seasoned oak from a managed forest to agent `a_2` (the carpenter), who produces and sells a finished table to a buyer `b`. The step-vectors recorded at each step (under §3.1's signed convention: extraction / consumption appears with negative components; labour incorporated is positive; zero components omitted):

`ΔV_1 = (v_1 = +12 h, v_3 = −8 kWh, v_4 = −0.005 m³ @ 15 °C, v_5 = −30 m²·day, v_6 = −100 kg oak)`

`ΔV_2 = (v_1 = +20 h, v_2 = −0.015 m³, v_3 = −25 kWh, v_9 = −0.2 g varnish residue)`

By Proposition G.A, the table sold to `b` carries

`V_total = ΔV_1 + ΔV_2 = (+32 h, −0.015 m³, −33 kWh, −0.005 m³ @ 15 °C, −30 m²·day, −100 kg oak, 0, 0, −0.2 g, 0)`.

The negative ecological components encode that the table embodies a chain of extraction (oak taken from the forest, fossil-fuel consumed in transport, energy and water spent in transformation, varnish residue released as pollutant). The positive `+32 h` records labour incorporated at the two steps — credited to the workers through ordinary mutual-credit transfer when the buyer pays.

Suppose the community has set the calibration `R_2 = 50` h/m^3 (water), `R_3 = 0.02` h/kWh (energy), `R_4 = 500` h/m^3 at 15 °C (fossil fuel), `R_5 = 0.001` h/(m^2·day) (surface), `R_6 = 0.005` h/kg (renewable resources), with pollutants and durability omitted in this minimal calibration, and `I_{p,v}(t_n) = 1.0` across the board. The day-`n` conversion on `b`'s ledger is computed component-wise from the signed inventory transferred at the sale:

Component	**`v_{b,j}` (signed)**	**`R_v`**	**`Rate_v · v_{b,j}` (h)**
Water (`v_2`)	−0.015 m^3	50 h/m^3	−0.75

Component	**$v_{b,j}$ (signed)**	**R_v**	**$Rate_v \cdot v_{b,j}$ (h)**
Energy (v_3)	−33 kWh	0.02 h/kWh	−0.66
Fossil fuel (v_4)	−0.005 m³ @ 15 °C	500 h/m³	−2.50
Surface (v_5)	−30 m²·day	0.001 h/(m²·day)	−0.03
Renewable (v_6)	−100 kg oak	0.005 h/kg	−0.50
Σ = $\Delta\theta_b^{conv}(n)$			**−4.44**

Separately, the buyer paid the chain 32 hours of labour — these hours pass to a_1 and a_2 as accounting transfers via the mutual-credit channel. The signed conversion reconciliation $\Delta\theta_b^{conv}(n) = -4.44$ h is added to θ_b against no offsetting credit at the close of day n.

If b enters the day with $\theta_b(t_{n-1}) = \Delta t = 8$ h (initial endowment, not in debt so $D_b(n) = 0$) and gives no labour that day:

$$S_b(n) = L_b^{paid}(n) + \max(0, -\Delta\theta_b^{conv}(n)) = 32 + \max(0, -(-4.44)) = 32 + 4.44 = 36.44 \text{ h}$$

$$D_b(n) = \max(0, -\theta_b(t_{n-1})) = \max(0, -8) = 0$$ (not in debt at start)

$$U_b(n) = \min(\Delta t, S_b(n) + D_b(n)) = \min(8, 36.44 + 0) = 8 \text{ h}$$ (capped)

$$\theta_b(t_n) = \theta_b(t_{n-1}) + L_b^{given} - L_b^{paid} + \Delta\theta_b^{conv} + U_b = 8 + 0 - 32 + (-4.44) + 8 = -20.44 \text{ h}.$$

The buyer is now in time-component debt of about 20 hours. UDI now flows to debt-paydown on subsequent days within the daily Δt cap. With zero further spending and zero labour given, the recursion runs as follows: on day $n+1$, $S = 0$, $D = 20.44$, $U = \min(8, 0 + 20.44) = 8$, so the balance rises from -20.44 to -12.44. On day $n+2$, $U = \min(8, 0 + 12.44) = 8 \rightarrow -4.44$. On day $n+3$, $U = \min(8, 0 + 4.44) = 4.44$ (capped at the remaining debt) $\rightarrow 0$. Debt clears in three idle days through residual UDI alone. If b additionally provides labour or consumes regenerative goods on these days, clearance accelerates proportionally.

The example is deliberately small but every construct of §§3.1–4.2 is visible. The simulator of §8 scales the same structure to 500 agents over five years, with heterogeneity, substitution, and time-varying I_p.

Annex H. Enterprise mechanics: cost-recovery, amortisation, owner compensation

This annex develops the operational mechanics that govern agents whose accumulated inventory represents work-in-progress or stock for sale rather than final consumption. The same vector-accounting rules of §§3–4 apply uniformly; this annex unpacks the cost-recovery pricing through which an enterprise's time-component balance returns to neutrality over each production-sale cycle.

H.1 The cost-recovery rule

An enterprise `e` maintains a running counter `cum_labour_paid[e]` recording the cumulative labour cost paid out to workers (via channel four, the `q_w`-weighted labour credit) and the cumulative labour cost paid out to upstream suppliers (the time-component of incoming purchased inventory). At each sale, the enterprise's time-component balance is credited:

```
θ_e += cum_labour_paid[e] · transfer_fraction
```

where `transfer_fraction` is the fraction of the enterprise's inventory transferred to the buyer at the sale (computed from the time-component of the transferred bundle divided by the time-component of the enterprise's accumulated inventory). The counter `cum_labour_paid[e]` is then decremented by the same amount: `cum_labour_paid[e] -= cum_labour_paid[e] · transfer_fraction`.

The mechanism makes the enterprise's selling price reflect the cumulative labour cost embedded in the goods sold — labour paid to workers in production plus labour-content of upstream inputs amortised over the units sold.

H.2 Capital amortisation

When an enterprise buys machinery, the machine's labour-content is included in `cum_labour_paid`. The enterprise then recoups it through sales over the machine's productive lifetime. If a machine costing 1,000 h of labour-content is purchased and used to produce 50,000 units over five years, each unit sold carries approximately 0.02 h of machine labour-content amortised, recouped at sale via the cost-recovery rule. The amortisation is implicit in the cost-recovery formula; no separate accounting horizon needs to be specified.

The ecological component of the machine's footprint travels with the machine into the enterprise's inventory and is **not** absorbed at reconciliation by the enterprise. It transfers to the buyers of the products produced with the machine, via the Contamination Principle: each unit sold carries its share of the machine's ecological footprint, propagating downstream until it reaches a final consumer who reconciles it on their household ledger.

H.3 Year-0 initialisation

At deployment, enterprises start with empty inventory and a time-component balance of zero. On day 1, the enterprise pays its first workers (debiting its balance) and replenishes raw-material inventory (incurring upstream labour-content debits and signed ecological-component inventory). Sales begin on day 2. During the production-before-sale gap, the enterprise's time-component balance is transiently negative — this is normal. As sales begin and cost-recovery credits flow in, the balance returns toward neutrality.

A persistently negative balance over multiple production cycles signals **demand failure**: the enterprise has overproduced relative to its market and should slow or stop production (paying fewer wages in subsequent cycles), not artificially amortise the loss over future prices. The framework does not amortise losses across future production; doing so would shift the cost of mis-pricing to future customers. The cost-recovery formula is mechanically equivalent to "the enterprise's selling price equals the cumulative labour cost of its inventory divided by the volume sold" — there is no room to inflate prices to recover past over-production.

H.4 Owner compensation channels

Business owners are compensated through one of two structurally bounded channels:

(i) **Real-time pointage**: hours actually worked are declared by the owner in real time, capped at 12 h per day. These hours flow into `cum_labour_paid` as ordinary labour credit and are recouped through future sales like any other worker's hours.

(ii) **Default 8 h per day**: an owner who does not pointage receives an arbitrary 8 h per day credit. This is the default for owners not engaged in active production; it acknowledges their role as designers, supervisors, or representatives without requiring time-tracking.

In either case, **accumulated time-component surplus in an enterprise's ledger is consumable only by future enterprise investment, not by individual withdrawal**. There is no mechanism by which an owner can extract enterprise surplus into their personal time-component balance, except through their declared pointage hours (capped). The framework forecloses individual extraction of enterprise surplus by construction — there is no mechanism to "pay out a profit", because there is no profit category and no shareholder claim.

Losses on enterprise balance are not socialised across other agents. If an enterprise sustains a persistent negative time-component balance, the corrective response is to slow production (pay fewer wages in subsequent cycles), not to inflate selling prices or transfer the loss elsewhere. The demand-side regulation is structural: customers who do not pay the labour-content of overproduced goods cause the enterprise to reduce output until balance returns.

H.5 Falsifiers at the operational layer

The framework's claim of structural enterprise neutrality (no profit, no loss-amortisation) is empirically falsifiable. Two patterns would constitute deployment-level evidence against the claim:

(F5a) **Enterprise-investment expenditures are systematically routed toward personal-asset acquisition** by owners or their affiliates. This would indicate that the surplus-consumption restriction is being bypassed through enterprise spending channels.

(F5b) **Enterprises consistently fail to reduce wage outlays when the time-component balance stays negative**, continuing to over-produce while owners draw their default 8 h per day. This would indicate that demand-side regulation is being suppressed, with the cost effectively transferred to UDI absorption across the community.

These complement §10.3 F5 at the simulation level and would inform the design of pilot evaluation criteria.