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Network-Lifted Digital Twins for Logistics: Feasible Pack Sets, Residue Spectra, Annealed Allocation, and Additive Attribution

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Abstract—
A supply-chain digital twin is treated here as a clock-aligned replica of plants, docks, lanes, inventories, and policies. This paper treats that replica as the network lift of a vehicle energy-store problem: pack polytopes, channel integrity, command latency, and solar harvest already define a feasible set; leftover charge after a stint is the same residual object as leftover pallets after an assignment. We write the twin state, an observer, a three-coordinate resilience vector, a disruption-aware assignment Hamiltonian, a two-sided shift identity that moves delayed residue pulses without leaving the test space, and a Shapley head that attributes service movement to pack, channel, harvest, and disruption features. The literature is organized as one regularized program: size the store, keep the channel observable, read the residual spectrum, twin the flow, anneal the allocation, and attribute leftovers so that delayed residue remains interchangeable with on-time residue.

Keywords: digital twin; supply-chain resilience; pack sizing; residual spectrum; ripple effect; quantum allocation; two-sided FKF transform; Shapley attribution; TreeSHAP; KernelSHAP

I. PROBLEM SETTING AND RESEARCH MOTIVE

Hybrid traction stores cannot be specified from ampere-hour ratings in isolation [11], [14], [15]. Usable energy, peak discharge, mass, bit-error rate on the integrity channel [12], and human-to-controller latency [13] shrink the feasible set to a polytope rather than an interval. Intelligent-transport and solar-assist architectures embed that polytope in a sense–plan–act loop whose binding constraints are connectivity, safety cases, and stochastic harvest [16], [17]. Once the vehicle is a node, leftover charge after a stint, leftover heat, and leftover pallets after a dock assignment are instances of one residual process whose band energy is an operational signature rather than measurement noise [18], [28], [29].

A digital twin is the object required to carry the same observer from cell voltages to warehouse gauges without a change of clock [22], [31]. Resilience is not mean flow; it is the vector of absorptive, recovery, and adaptive capacities, and digital transformation raises observability of that vector rather than the vector itself [23]–[25]. Unit-load configuration and disruption recovery remain set-partition problems; annealing and hybrid variational candidates score assignment energy, but leftover inventory parked on a soon-to-fail node is invisible unless the Hamiltonian is residue-aware [19], [26], [27]. Green-logistics learners already dominate published flow prediction; Shapley credits then attribute a residual to pack mass, harvest, latency, or disruption masks without breaking additivity [20], [21].

The contribution of this article is therefore not another isolated estimator. It is a map that (i) keeps delayed leftovers interchangeable with on-time ones through a two-sided FKF shift [28], [29], (ii) scores allocation on leftover load as well as assignment cost [27], and (iii) writes every named object—pack polytope, channel cut, harvest forecast, replica, resilience vector, Hamiltonian, residual spectrum, two-sided shift, and Shapley vector so that a later measurement campaign can log them on one clock [11]–[29]. Figure 1 states

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the stack. The remainder of the paper reviews the source literature (Section II), writes the coupled objects (Section III), specifies Shapley attribution on the twin (Section IV), records measurement gaps and a reporting convention (Section V), and concludes (Section VI).

Figure 1. Coupled sizing–channel–harvest–twin–allocation–attribution stack. Objects [11]–[29] are required to share one clock.

II. SURVEY OF THE COUPLED LITERATURE

A. Pack design bounds and cell-level observers

Closed-form hybrid sizing studies pin usable energy, peak discharge, and mass in a single cut [11]. Cell-material and management reviews replace the scalar usable energy with a state that includes fade, thermal headroom, and leftover energy after the cycle [14], [15]. A linear observer on state of charge, polarization voltages, and a fade parameter is the information geometry later reused by network twins that ingest warehouse and lane gauges [22]. Thermal headroom is an inequality constraint, not a soft penalty, because a single over-temperature event censors the rest of the duty cycle [15]. Channel violations inject packet-drop processes into the measurement and inflate the innovation; power-line and radio traces used in anti-theft settings are impulsive rather than Gaussian [12]. Latency of a swipe-style torque map is operationally equivalent to a missing energy quantum and, to first order, to a time shift of the residual treated below [13], [28].

B. Transport policy, harvest slack, and closed loops

Surveys of intelligent mobility embed the sized pack inside a sense–plan–act loop whose binding constraints are connectivity, safety cases, and data rights [16]. Solar-assisted architectures add a stochastic generation term to the discrete energy balance [17]. Pack undersizing is admissible only if policy can forecast harvest and demand jointly and if the integrity channel still carries the forecast [12], [16]. Policy sensitivity along harvest features means the stack is betting on solar slack; those bets must be logged if solar-assist is to be audited [17]. Large components along disruption masks mean the policy is already doing part of the allocator's work [23], [25].

C. Replicas, ledgers, and cascading disruption

Foundational twin definitions treat a supply-chain replica as a model that can represent network state at any given moment and allow complete end-to-end visibility to improve resilience and test contingency plans [30], [31]. The ripple effect occurs if a disruption cannot be localized and cascades downstream into sales, service, and cost [30]. AI-plus-ledger designs treat shipment and state-of-charge traces as append-only records so that substitution events remain auditable [21]. A live replica must carry the cell observer up to lane and warehouse coordinates [22]. Systematic reviews of digital-era resilience list that joint observation as an open agenda item and map twin services onto preparedness, resistance, rebound, and growth [23]–[25]. Data quality, partner unwillingness to share, skill shortages, and governance remain binding barriers [24], [25].

D. Set-partition assignment and residue-aware costs

Load-device configuration and disruption recovery remain set-partition problems whose classical neighbourhood search misses deep local minima [27]. Quantum-logistics notes collect annealing, amplitude amplification, and hybrid variational candidates [19], [26]. Scoring annealers only on assignment energy hides leftover inventory parked on a soon-to-fail node. A disruption-aware cost adds a leftover term that rises with the disruption mask [27]. Connecting that cost to the mobility policy is straightforward on paper and rare in deployments: the assignment becomes part of the feature that policy re-solves [16], [19].

E. Shift-stable residue maps on test-function spaces

Residue extraction across hybrid-vehicle and warehouse traces is a transform-domain claim, not only a filter design [18]. The two-sided FKF transform acts on a test-function space in which a time shift becomes a structured multiplier, so a delayed leftover can be moved through the same pipeline as an on-time pulse [28]. Sequential convergence in the test-function space justifies interchanging limit and pairing when residue pulses arrive one shock at a time [29]. Fractional-Fourier product and convolution identities supply the algebraic background for reading band energy of leftovers [32]–[35]. Annealed assignments enter as piecewise-constant flows; a jump must be subtracted before the spectrum is read as a fade signature, otherwise a dock event is attributed to chemistry [18], [27].

F. Additive credit assignment on the replica

Bibliometric maps of green logistics show that supervised and ensemble learners already dominate published flow-prediction work [20]. Once a model

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maps route, pack, and disruption features to energy, delay, or service, Shapley credits attribute the residual to pack mass, harvest, latency, or disruption masks without breaking additivity [20], [21]. Tree ensembles common in the logistics corpus are the natural host for TreeSHAP; twins supply the background measure against which coalition values are estimated [22]. A reporting convention consistent with the stack is to publish, for each explained instance, the Shapley vector beside the resilience vector. Large latency credit with small adaptive capacity says the interface, not the pack, moved service [13], [16]. Large leftover credit with small assignment energy says the annealer cheapened the Hamiltonian while parking residue [27].

G. Open measurement issues and joint agenda

Three gaps follow from the cited chain. First, pack sizing and cell-management reviews still publish few open duty-cycle tables that a twin could ingest without hand alignment [11], [14], [15], [22]. Second, quantum allocation notes rarely close the loop to an FKF residual, so annealed assignments are scored on assignment energy and not on leftover spectra or resilience [19], [26], [27], [28]. Third, resilience vectors are seldom estimated with the same observer used for pack state, which breaks the information geometry of the cell observer [14], [23], [25]. A joint agenda is therefore: publish coupled energy–flow corpora with channel-quality stamps [12]; score annealers on residue spectra and on resilience [18], [27]; and attach Shapley heads to twin updates so that adaptive capacity is inspectable [20], [21].

III. OBJECTS SHARED ON A SINGLE CLOCK

A. Feasible pack set and weighted scalarization

Traction energy on the prescribed cycle, hotel load, stint length, and the reserve demanded by the safety case jointly bound usable energy. Admissibility of usable energy is the cut$E_{tr} E_h \Delta t E_{res} E_u$

$$E_u \geq E_{tr} + E_h \, \Delta t + E_{res}$$

Mass M and peak power P_{pk} add two further inequalities, so the design point is a vector rather than a scalar [14], [15]. Channel integrity and command latency enter as coupled limits. If $I(s;\, \hat{s})$ is the mutual information between the true pack–controller state and the broadcast, a valid update requires

$$I(s;\, \hat{s}) \geq I_{min}$$

with bit-error rate and carrier capacity setting the feasible region [12]. Latency of a swipe-style map is treated as a missing energy quantum and as a shift of $r(t)$ [13], [28]. A compact scalarization used throughout is the weighted objective

$$J = w_1 J_E + w_2 J_M + w_3 J_P + w_4 J_{ch} + w_5 J_{lat} + w_6 \rho$$

with nonnegative weights summing to one and ρ a normalized leftover after the duty cycle. Minimizing J recovers the Formula-hybrid cut when the channel and latency weights vanish [11], and recovers the communication-aware pack when those weights are restored [12], [13]. Leftover capacity is not scrap; it is the seed of the residual spectrum [18].

B. Band energy of leftovers and two-sided transport

Leftover charge written as a function on the duty-cycle clock admits a Fourier-type band energy$r(t)$

$$\int |T\{r\}(\omega)|^2 \; W(\omega) \, d\omega$$

where T is the two-sided FKF transform [18], [28], [29], [32]–[35]. Peaks are treated as operational signatures—fade bands, delayed shipments, leftover heat—rather than as measurement noise. If $r_\tau(t) = r(t - \tau)$ is a delayed leftover, the shift identity

$$T\{r_\tau\} = M_\tau \, T\{r\}$$

moves that pulse through the same pipeline as an on-time leftover without leaving the test space [28]. Sequential convergence justifies interchanging limit and pairing when shocks arrive one at a time [29].

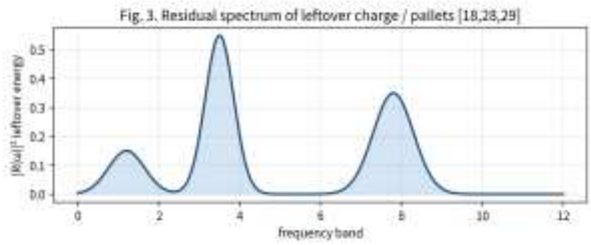


Figure 3. Schematic residual spectrum of leftover charge and leftover pallets. Band peaks are logged as operational signatures [18], [28], [29].

C. Replica coordinates and the three-axis resilience vector

The replica state is written as

$$\Phi = (\hat{x}, \xi, \pi)$$

where $\hat{x}$ is the cell observer, ξ a network disturbance (lane closure, harvest drought, dock mask), and π a policy or assignment [22], [31]. Coupling fails when Φ is updated on a different clock from the pack observer [14], [22]. Resilience is the vector

$$R = (A, B, \gamma)$$

of absorptive, recovery, and adaptive capacities [23]–[25]. A schematic service path after a shock at t^* decays and then rebounds; digital transformation raises observability of (A, B, γ) but does not by itself raise them. Ledgers make the path auditable [21]; twins make it forecastable [22]; resilience reviews insist that all three coordinates be reported rather than a single uptime percentage [23], [25].

Figure 2. Service path after a shock. Absorptive capacity sets the drop, recovery the rebound slope, adaptive capacity the new plateau [23]–[25].

D. Disruption-aware assignment energy

A compact assignment energy for loads on devices isℓd

$$H = \sum_{\ell,d} c_{\ell d}\, z_{\ell d}$$

plus linear penalties for capacity and disruption masks, with binary $z_{\ell d}$ [19], [27]. The disruption-aware cost used here is

$$H' = H + \sum_{d} \lambda_d\, \rho_d$$

where ρ_d is leftover inventory on device d and λ_d rises with the disruption mask [27]. That leftover is the discrete analogue of ρ in the pack scalarization and of $r(t)$ in the spectrum [18]. Quantum and hybrid annealing remain candidates for searching H' [19], [26], [27]; they are scored here on leftover load and on R, not on H alone.

IV. ADDITIVE ATTRIBUTION ON THE REPLICA

A. Features, coalition value, and uniqueness axioms

Features logged on the twin clock include pack mass and usable energy [11], [14], [15], channel quality and latency [12], [13], harvest [17], disruption masks [23], assignment cost, and leftover [18]. For a predictive map from those features to energy, delay, or service [20], the coalition value is the expected output when only features in a coalition are known and the complement is drawn from a background measure supplied by the replica [22]. The Shapley credit

$$\varphi_i = \sum_{S \subseteq N\setminus\{i\}} \frac{|S|!\,(|N|-|S|-1)!}{|N|!}\,[v(S \cup \{i\}) - v(S)]$$

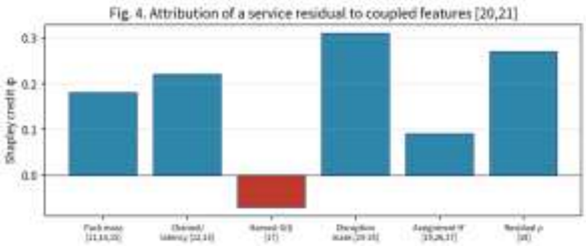
is the unique efficient, symmetric, dummy-respecting, additive allocation of $f(x) - E[f]$ [20], [21]. Efficiency is what lets φ sit beside R without a change of units: the sum of credits recovers the residual that R is asked to absorb.

B. Estimators aligned with the coupled stack

Tree ensembles dominate the green-logistics corpus [20], so interventional TreeSHAP is the default host: polynomial in trees, leaves, and depth, deterministic given the forest and the twin background. When the predictor is a mixed pipeline (observer plus annealer plus service head), KernelSHAP or a propagated DeepSHAP-style rule is required so that credits still sum to the residual [21]. Conditional games keep dependence among harvest and demand; interventional games answer "what if this mask is set?" Both are admissible; the twin must name which game was solved [22]. Grouping features into pack, channel, harvest, mask, assignment, and leftover blocks keeps the coalition count inside an audit budget.

C. Reading credits against resilience and assignment cost

Credits are read jointly with the resilience vector and the disruption-aware cost. Large on latency with small adaptive capacity says the interface, not the pack, moved service [13], [16], [25]. Large on leftover with small says the annealer cheapened assignment while parking residue [27]. Large on harvest with small absorptive capacity says the stack is betting on [17]. Interaction (Shapley–Owen) terms capture pack × disruption products that additive would split incorrectly [20]. Every explained instance stores next to on the ledger [21].



V. FIELD PROTOCOL AND LOGGING CONVENTION

No new physical layer is required for the named objects. They require that pack polytope [11], [14], [15], channel cut [12], latency [13], harvest forecast [17], replica [22], vector [23]–[25], Hamiltonian [19], [26], [27], residual spectrum [18], [28], [29], and Shapley vector [20], [21] be logged on one clock and scored with one residual language. A single stint walks the stack as follows: pack state and channel quality; harvest forecast; assignment from a low-energy band; ledger stamp; optional shift; pairing against a feeder probe; update of the replica; storage of credits beside the resilience vector so that failure modes remain localizable.

Until coupled energy flow corpora with channel-quality stamps exist, each layer can be locally correct and globally incomparable [11], [12], [22]. Until annealers are scored on residue spectra and on resilience, cheap assignment energy will continue to hide parked leftovers [27], [28]. Until Shapley heads ride twin updates, adaptive capacity will remain an inspectable scalar [20], [21], [25].

VI. CLOSING REMARKS

A supply-chain digital twin was written as the network lift of a vehicle energy-store problem. Pack polytopes, channel integrity, command latency, and solar harvest define a feasible set; leftover charge and leftover pallets are one residual process whose spectrum is an operational signature. The replica carries one observer from cells to docks; resilience is reported as the three-coordinate vector rather than as uptime; allocation is scored on the disruption-aware Hamiltonian and leftover load; Shapley credits attribute service movement without breaking additivity. Delayed leftovers remain interchangeable with on-time leftovers because the two-sided shift stays inside the test space. The measurement agenda is to publish the named objects on one clock so that operational audits see the same citation chain that the twin itself uses.

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