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A TROPICAL MULTI-SEMIRING FRAMEWORK FOR EVALUATING MSME DIGITAL FINANCING PATHWAYS

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Abstract
Digitalization expands financing options for micro, small, and medium enterprises (MSMEs), yet each pathway presents a different configuration of cost, dependence, inclusion, and resilience. This study develops a tropical multi-semiring framework for evaluating banks, independent fintech providers, platform lending, Digital Credit Unions, and managed hybrid pathways under common rules. Five MSME profiles are calibrated using financing-need categories from Bank Indonesia's BISAID database and constraint characteristics reported by Statistics Indonesia; detailed provider and intervention parameters remain computational scenarios. Cost is evaluated through weighted accumulation and min-plus route selection, dependence through a maximum-based Tropical Financing Dependence Index, and inclusion and resilience through weakest-link operations. The resulting architecture is monotone under no-harm interventions, Pareto-consistent for nonnegative weights, and Lipschitz-stable to normalized perturbations. Baseline advantages are distributed: platform lending has the lowest cost, banks the lowest dependence, and the hybrid pathway the highest resilience. After adaptive three-intervention packages, Digital Credit Unions are most robust for four profiles, whereas the hybrid pathway is most robust for manufacturing; banks nevertheless retain distinct choice regions. Recommendations should therefore be profile-specific and transparent about assumptions.
Keywords: *MSMEs; digital finance; multi-semiring; tropical algebra; financing dependence.*

1. Introduction

Digitalization has become an important component of the transaction and financing infrastructure available to MSMEs. In the first quarter of 2026, QRIS acceptance reached approximately 44 million merchants, most of which were MSMEs, indicating that digital payment footprints have become increasingly extensive and may support creditworthiness assessment (Bank Indonesia, 2026a). Transaction data, cash-flow records, and service integration can reduce information asymmetry, accelerate verification, and broaden financing access for businesses that lack conventional collateral or an adequate formal credit history (Bank Indonesia, 2024; Teima et al., 2022).

Greater access does not imply that all financing pathways provide the same institutional quality. Banks may offer stability and prudential oversight, but their procedures can be burdensome for microenterprises. Independent fintech providers and platform lenders may accelerate disbursement, yet can increase dependence on data, payment channels, algorithms, market access, or technology vendors. Digital Credit Unions may strengthen member-based relationships, but still face digitalization costs, scale constraints, and vendor-dependence risks. Managed hybrid pathways may combine institutional strengths, although their effectiveness depends on contracts, interoperability, risk allocation, and partner substitutability.

Financing evaluation therefore cannot be reduced to a comparison of interest rates. Administrative charges, approval time, documentation burdens, collateral, data dependence, switching costs, accessibility, transparency, continuity, and recovery must be considered together. A single average can conceal a critical weakness: one pathway may be inexpensive but highly dependent, while another may be inclusive but insufficiently resilient. A suitable framework must preserve the distinct logic of each dimension before combining them at the decision stage.

Bank Indonesia's BISAID database provides profiles of MSMEs seeking development financing, while Statistics Indonesia's *Profile of Micro and Small Industries 2024* supplies official context concerning capital, business constraints, internet use, and marketing (Bank Indonesia, n.d.; Statistics Indonesia, 2025). These sources do not report every cost, platform-dependence, inclusion, resilience, and intervention variable for the same observational units. This study therefore adopts a methodological-computational design that combines officially calibrated profiles with explicitly labeled scenario parameters. The approach is more realistic than a purely illustrative example, but it is not presented as an empirical population estimate for Indonesian MSMEs.

The study addresses three questions. First, how do five financing pathways differ in cost, dependence, inclusion, and resilience across heterogeneous MSME profiles? Second, how do institution-neutral interventions change critical dependence sources and financing-autonomy margins? Third, which pathways remain preferable under different policy weights and feasibility thresholds? The contributions are: (1) a dimension-preserving multi-semiring evaluation; (2) the Tropical Financing Dependence Index (TFDI), Tropical Financing Autonomy Margin (TFAM), and Comparative De-locking Effect (CDE) as diagnostic tools; (3) integration of officially calibrated profiles with transparent computational scenarios; (4) symmetric comparison under common thresholds, interventions, tie rules, and sensitivity procedures; and (5) formal bounds, monotonicity, Pareto consistency, existence, perturbation stability, and piecewise-linear weight dependence.

2. Literature Review

2.1 Digital finance, transaction costs, and MSME heterogeneity

Digital finance can reduce search, verification, and coordination costs, consistent with transaction-cost and MSME-digitalization perspectives (Williamson, 1985; OECD, 2021). Alternative data allow financial institutions to infer business activity from payments, sales, or supply chains, so decisions need not rely exclusively on conventional collateral. Bank Indonesia (2024) emphasizes the importance of innovative digital-financing models while recognizing that models must match business needs and capabilities. Consequently, disbursement speed, collateral, and financing price receive different importance for rural producers, marketplace traders, manufacturers, digital-service firms, and community suppliers.

2.2 Ecosystem dependence and contestability

Digital ecosystems connect financing to data, payments, markets, visibility, and logistics (Adner, 2017; Chen et al., 2022). Platforms provide access to these resources but may create power asymmetries when rules, reputations, and customer relationships are not portable (Cutolo & Kenney, 2021; Yu & Sekiguchi, 2024). Dependence is not identical to platform use; it becomes problematic when an MSME lacks a realistic alternative, faces high switching costs, or loses data and reputation upon exit. Data portability and open finance can improve contestability, but require interoperable standards, security, meaningful consent, and alternative providers capable of using transferred data (OECD, 2024; Bank for International Settlements, 2026).

2.3 Institutional pathways and resilience

Banks, fintech providers, platforms, Credit Unions, and hybrid partnerships represent different governance arrangements rather than a predetermined quality ranking. Resource-dependence theory explains how organizations manage reliance on actors controlling critical resources (Pfeffer & Salancik, 2003). Organizational resilience includes capacities to anticipate, cope with, and adapt to disruption (Duchek, 2020). In MSME finance, resilience concerns channel redundancy, interoperability, service continuity, recovery, and partner substitutability. Cooperative principles may support member control and inter-organizational collaboration (International Cooperative Alliance, n.d.), but any advantage is realized only when translated into digital capacity, data governance, security, and viable vendor choice (World Council of Credit Unions, 2025).

2.4 Tropical algebra and coordinated multi-semiring evaluation

Let $E_{\min}$ and $E_{\max}$ denote the min-plus and max-plus layers on the extended real line. Their idempotent additions and common ordinary-additive product are

$$x \oplus_{\min} y = \min\{x, y\}, \qquad x \oplus_{\max} y = \max\{x, y\}, \qquad x \otimes y = x + y. \tag{1}$$

Minimum or maximum selects among competing alternatives, whereas ordinary addition accumulates sequential burdens (Baccelli et al., 1992). Inclusion and resilience use the meet operation on the unit interval,

$$([0,1], \wedge), \qquad x \wedge y = \min\{x, y\}. \tag{2}$$

A meet operation alone is not a full semiring. Therefore, the term *multi-semiring* is used operationally for a coordinated product of dimension-specific ordered structures, not to claim that the entire product is one semiring. This preserves each aggregation law and connects the outputs only afterward through a common burden order and a weighted Chebyshev map, consistent with multi-metric idempotent modeling (Somasundaram & Baras, 2011).

$$\mathcal{S} = \mathcal{E}_{\min} \times \mathcal{E}_{\max} \times ([0,1], \wedge) \times ([0,1], \wedge), \tag{3}$$

3. Research Methods

3.1 Design, data sources, and calibration

The study uses a methodological-computational design. Financing-need ranges are calibrated using BISAID categories, and constraint characteristics are constructed with reference to BISAID, Statistics Indonesia (2025), and Bank Indonesia (2024). Each item is labeled as official data, calibrated profile, scenario parameter, or model output. Official data improve profile realism but do not convert the five profiles into five observed firms. Provider prices, administrative burdens, approval time, documentation, collateral, dependence, inclusion, resilience, readiness, and intervention effects remain transparent computational parameters.

Table 1. Calibrated MSME profiles and principal constraints

Code	Profile	Financing need	Principal constraints
h_1	Rural micro food producer	IDR 10-50 million	Working capital, documentation, raw materials, logistics
h_2	Female marketplace trader	IDR 10-50 million	Working capital, digital visibility, payments, switching cost
h_3	Small processing/manufacturing firm	Above IDR 100 million	Working capital/investment, collateral, technology, continuity
h_4	Creative or digital-service firm	IDR 50-100 million	Alternative data, payments, reputation, interoperability
h_5	Community-based commodity supplier	Above IDR 100 million	Inventory, logistics, coordination, alternative market channels

Source: authors' calibration based on Bank Indonesia's BISAID, Statistics Indonesia (2025), and Bank Indonesia (2024); profiles are not five individual firms.

The alternative set comprises banks, independent fintech providers, platform lending, Digital Credit Unions, and managed hybrid pathways. The evaluation dimensions and operators are summarized below.

Table 2. Dimension-specific aggregation and decision meaning

Dimension	Source components	Aggregation rule	Direction
Cost	Price, administration, time, documentation, collateral burden	Weighted sum within each route; minimum across admissible routes	Lower is better
Dependence	Data, payment, algorithm, vendor, market-channel exposure	Maximum critical source (TFDI)	Lower is better
Inclusion	Accessibility, usability, transparency, appeal	Meet/weakest link	Higher is better
Resilience	Continuity, interoperability, recovery, redundancy	Meet/weakest link	Higher is better
Policy comparison	Common burden vector	Weighted Chebyshev maximum	Lower is better

Source: authors' specification based on Baccelli et al. (1992) and Somasundaram and Baras (2011).

3.2 Common state, feasibility, and dominance

For profile h and pathway a, define the evaluation state and the common burden vector by

$$X_{ha} = (C_{ha}, D_{ha}, I_{ha}, R_{ha}), \qquad b_{ha} = (C_{ha}, D_{ha}, 1 - I_{ha}, 1 - R_{ha}). \tag{4}$$

The common order is componentwise minimization,

$$b_{ha} \preccurlyeq b_{hb} \Leftrightarrow b_{ha,j} \leq b_{hb,j} \quad (j = 1, \dots, 4). \tag{5}$$

For threshold vector $\theta = (\bar{C}, \bar{D}, \underline{I}, \underline{R})$, the feasible set is

$$\mathcal{F}_h(\theta) = \{a: C_{ha} \leq \bar{C},\ D_{ha} \leq \bar{D},\ I_{ha} \geq \underline{I},\ R_{ha} \geq \underline{R}\}. \tag{6}$$

Within the same profile-specific decision space, pathway a weakly dominates b when

$$a \preccurlyeq_h b \Leftrightarrow b_{ha} \preccurlyeq b_{hb}, \qquad b_{ha} \neq b_{hb}. \tag{7}$$

3.3 Dimension-specific indicators and final envelope

Cost components are normalized against fixed anchors. Within route r, they accumulate through a weighted ordinary sum, while the minimum across admissible routes implements min-plus selection:

$$C_{ha} = \min_{r \in \mathcal{R}_{ha}} \left(\sum_{\ell=1}^{m_r} \alpha_{r\ell}\, n_{ha,r\ell} \right), \qquad \alpha_{r\ell} \geq 0, \quad \sum_{\ell} \alpha_{r\ell} = 1. \tag{8}$$

Dependence is the maximum normalized exposure,

$$D_{ha} = \mathrm{TFDI}_{ha} = \max_{1 \leq j \leq p} d_{ha,j}. \tag{9}$$

Inclusion and resilience follow weakest-link aggregation,

$$I_{ha} = \min_{1 \leq j \leq q} i_{ha,j}, \qquad R_{ha} = \min_{1 \leq j \leq r} r_{ha,j}. \tag{10}$$

Autonomy capacity and its margin from the healthy threshold $\tau = 0.50$ are

$$A_{ha} = \min\{1 - D_{ha}, I_{ha}, R_{ha}\}, \qquad \mathrm{TFAM}_{ha} = A_{ha} - \tau. \tag{11}$$

For $w = (w_C, w_D, w_I, w_R)$ on the nonnegative simplex, the weighted Chebyshev envelope is

$$\Omega_w(b_{ha}) = \max\{w_C C_{ha}, w_D D_{ha}, w_I(1 - I_{ha}), w_R(1 - R_{ha})\},\ w_j \geq 0, \quad \sum_j w_j = 1. \tag{12}$$

3.4 Adaptive three-intervention packages and readiness

Let $\mathcal{H} = \{h_1, \dots, h_5\}$, $\mathcal{A} = \{B, F, P, CU, H\}$, and $\mathcal{K} = \{K_1, \dots, K_8\}$. The candidate package set is

$$\mathfrak{P}_3 = \{P \subseteq \mathcal{K} : |P| = 3\}, \qquad |\mathfrak{P}_3| = \binom{8}{3} = 56, \quad 5 \times 5 \times 56 = 1{,}400. \tag{13}$$

The interventions are data and reputation portability (K_1), payment interoperability (K_2), alternative-data scoring (K_3), transparency and appeal mechanisms (K_4), vendor substitution and exit planning (K_5), multi-homing and channel redundancy (K_6), shared or modular infrastructure (K_7), and managed hybrid partnership (K_8). Every capability is available to every institutional alternative under the same definition and nominal intensity.

For the present experiment, institutional readiness is a primitive scenario coefficient,

$$\rho_{hak} \in [0,1], \qquad h \in \mathcal{H},\ a \in \mathcal{A},\ k \in \mathcal{K}, \tag{14}$$

representing the realizable fraction of intervention k for profile h through pathway a. It is not an official institutional rating or a permanent quality score. Future calibration may decompose readiness into profile relevance, implementation capacity, and interface compatibility, but that decomposition is not claimed to have generated the present tables.

Let $Z_{ha} \in [0,1]^s$ collect all normalized source components, u_k be nominal intensity, and Δ_k be the signed source-effect vector. Package P first updates source components,

$$Z_{ha}^P = \Pi_{[0,1]^s}(Z_{ha} + \textstyle\sum_{k \in P} \rho_{hak}\, u_k \Delta_k), \tag{15}$$

and then recomputes C, D, I, R, TFAM, and the burden vector. A candidate is retained only when

$$C_{ha}^P \leq C_{ha}, \quad D_{ha}^P \leq D_{ha}, \quad I_{ha}^P \geq I_{ha}, \quad R_{ha}^P \geq R_{ha}. \tag{16}$$

With equal weights $w^{(0)} = (1/4, 1/4, 1/4, 1/4)$, the adaptive package set is

$$\mathfrak{P}_{ha}^{\mathrm{opt}} = \underset{P \in \mathfrak{P}_{ha}^{NH}}{\arg\min} \Omega_{w^{(0)}}\big(b_{ha}^P\big). \tag{17}$$

All minimizers are optimal; a table may display one representative when several packages tie. The Comparative De-locking Effect measures reduction in the critical dependence source,

$$\mathrm{CDE}_{ha}^P = D_{ha} - D_{ha}^P. \tag{18}$$

3.5 Independent weight and threshold audits

Preference sensitivity uses the tenths grid

$$\mathcal{W} = \left\{\left(\frac{m_1}{10}, \dots, \frac{m_4}{10}\right) : m_j \in \mathbb{Z}_{\geq 0},\ \textstyle\sum_{j=1}^4 m_j = 10\right\}, \qquad |\mathcal{W}| = \binom{13}{3} = 286. \tag{19}$$

At the nominal threshold, after feasibility and Pareto screening, the winner set is

$$\mathcal{M}_h(w) = \underset{a \in \mathcal{N}_h(\theta^{(0)})}{\arg\min}\ \Omega_w\big(b_{ha}^{\mathrm{opt}}\big). \tag{20}$$

A tie divides one credit equally, and the percentage frequency is

$$\kappa_{ha}(w) = \begin{cases} |\mathcal{M}_h(w)|^{-1}, & a \in \mathcal{M}_h(w), \\ 0, & a \notin \mathcal{M}_h(w), \end{cases} \qquad f_{ha} = \frac{100}{286} \sum_{w \in \mathcal{W}} \kappa_{ha}(w). \quad (21)$$

Feasibility sensitivity is a separate audit. With three levels for each of four thresholds,

$$\mathcal{T} = T_C \times T_D \times T_I \times T_R, \qquad |\mathcal{T}| = 3^4 = 81. \quad (22)$$

The percentage of tested regimes in which an adaptive pathway remains feasible is

$$\phi_{ha}(\theta) = \mathbf{1}\left[C_{ha}^{\text{opt}} \le \bar{C},\ D_{ha}^{\text{opt}} \le \bar{D},\ I_{ha}^{\text{opt}} \ge \underline{I},\ R_{ha}^{\text{opt}} \ge \underline{R}\right], \qquad g_{ha} = \frac{100}{81} \sum_{\theta \in \mathcal{T}} \phi_{ha}(\theta). \quad (23)$$

The 286 weight vectors are not nested in the 81-threshold loop. If $n_H, n_A, n_K, q, s, r, n_W, n_T$ denote the numbers of profiles, alternatives, interventions, interventions per package, source components, route components, weight vectors, and threshold combinations, the corrected worst-case time is

$$T = O\left(n_H n_A \binom{n_K}{q} (s + r) + n_H (n_A^2 + n_W n_A + n_T n_A)\right). \quad (24)$$

The fixed design is computationally small; combinatorial growth becomes important only when the intervention catalogue or package size expands.

3.6 Mathematical properties of the decision architecture

The following results concern internal model consistency, not empirical validity of the scenario parameters.

Lemma 1 (idempotent route selection). Duplicating an admissible route does not change the selected cost, and adding a new route cannot increase it:

$$\min(C_1, \dots, C_m, C_j) = \min(C_1, \dots, C_m), \qquad \min(C_1, \dots, C_m, C_{m+1}) \le \min(C_1, \dots, C_m). \quad (25)$$

Proof. Minimum is idempotent, and the minimum over an enlarged set cannot exceed the previous minimum. This justifies min-plus language across routes, while weighted ordinary accumulation remains within a route.

Proposition 1 (bounds). For normalized indicators and $\tau \in [0,1]$,

$$0 \le A_{ha} \le 1, \qquad -\tau \le \text{TFAM}_{ha} \le 1 - \tau. \quad (26)$$

Proof. The three arguments $1 - D_{ha}$, I_{ha}, and R_{ha} lie in [0,1]; their minimum therefore lies in the same interval.

Proposition 2 (no-harm monotonicity). If a package satisfies Equation (16), then for every nonnegative policy weight,

$$b_{ha}^P \preccurlyeq b_{ha}, \qquad \Omega_w(b_{ha}^P) \le \Omega_w(b_{ha}), \qquad \text{TFAM}_{ha}^P \ge \text{TFAM}_{ha}. \quad (27)$$

Proof. Each burden component cannot increase. Nonnegative multiplication and the maximum preserve componentwise order. The minimum defining autonomy cannot decrease. Strict improvement is not guaranteed when a changed component is nonbinding.

Proposition 3 (Pareto consistency). For two pathways in the same profile,

$$b_{ha} \preccurlyeq b_{hb} \Rightarrow \Omega_w(b_{ha}) \leq \Omega_w(b_{hb}) \quad \forall\, w \geq 0. \tag{28}$$

Proof. Multiplication by nonnegative weights and the maximum preserve the componentwise inequality. Hence Pareto filtering cannot remove a pathway with a strictly smaller envelope than its dominator.

Proposition 4 (existence). If the feasible nondominated set $\mathcal{N}_h(\theta)$ is finite and nonempty, then

$$\arg\min_{a \in \mathcal{N}_h(\theta)} \Omega_w(b_{ha}) \neq \varnothing. \tag{29}$$

Proof. A real-valued function on a finite nonempty set attains a minimum. Proportional tie allocation is a reporting convention, not an existence assumption.

Proposition 5 (perturbation stability). For burden vectors b and $\tilde{b}$,

$$\left|\Omega_w(b) - \Omega_w(\tilde{b})\right| \leq \| w \odot (b - \tilde{b}) \|_\infty \leq \| b - \tilde{b} \|_\infty. \tag{30}$$

Proof. The difference between two maxima is bounded by the maximum componentwise difference. Thus, if every normalized burden component has absolute error at most ε, the envelope error is at most ε; under equal weights, the sharper bound is $\varepsilon/4$.

Corollary 1 (piecewise-linear weight dependence). For fixed b, $w \mapsto \Omega_w(b)$ is convex, continuous, and piecewise linear. Its active-component boundaries satisfy

$$w_j b_j = w_\ell b_\ell, \qquad j \neq \ell. \tag{31}$$

Consequently, winning pathways can change across finitely many weight regions without discontinuity in any pathway's score.

3.7 Worked calculation and computational sequence

Table 3. Reconstruction of the aggregate Bank baseline calculation

Stage	Scenario inputs	Calculation	Output
Cost	$n_1 = 0.440;\ n_2 = 0.300;\ n_3 = 0.500$ $n_4 = 0.360;\ n_5 = 0.505;\ \alpha = 0.20$	$C = 0.20 \times (0.440 + 0.300 + 0.500 + 0.360 + 0.505) = 0.421$	$C = 0.421$
Dependence	$d_1 = 0.210;\ d_2 = 0.348$ $d_3 = 0.250;\ d_4 = 0.180;\ d_5 = 0.300$	$D = max(d)$	$D = 0.348$
Inclusion	$i_1 = 0.720;\ i_2 = 0.640$ $i_3 = 0.560;\ i_4 = 0.680$	$I = min(i)$	$I = 0.560$
Resilience	$r_1 = 0.700;\ r_2 = 0.620$ $r_3 = 0.650;\ r_4 = 0.680$	$R = min(r)$	$R = 0.620$
Autonomy	$1 - D = 0.652;\ I = 0.560$ $R = 0.620$	$A = min(0.652; 0.560; 0.620)$ $TFAM = A - 0.500$	$A = 0.560$ $TFAM = +0.060$
Feasibility	$\theta = (0.75; 0.75; 0.35; 0.40)$	All four inequalities satisfied	Feasible
Equal-weight envelope	$w = (0.25; 0.25; 0.25; 0.25)$	$\Omega = max(0.10525; 0.08700; 0.11000; 0.09500)$	$\Omega = 0.110$
Adaptive summary	$Baseline\ TFAM = 0.060$ $Adaptive\ TFAM = 0.157$	$Gain = 0.157 - 0.060$	$+0.097$

Source: authors' calculation. The cost-component vector is an explicit computational decomposition selected to reproduce the aggregate Bank row; it is not an additional empirical observation.

The program first evaluates 25 baseline cases. For every case, it enumerates 56 three-intervention packages and produces 1,400 candidate evaluations before no-harm screening. Surviving packages are ranked by the equal-weight envelope. The resulting adaptive states are then evaluated in two independent procedures: 286 weight vectors at the nominal threshold and 81 threshold combinations for feasibility. Ties divide one decision credit equally.

Design objectivity is supported by five procedures: common dimensions and anchors; the same eight capabilities and package size; no institutional bonus or penalty; explicit treatment of the hybrid alternative and ties; and profile-, weight-, and threshold-specific reporting. These procedures reduce structural bias but do not remove scenario uncertainty.

4. Research Findings and Discussion

4.1 Baseline conditions

No pathway dominates every dimension. Platform lending records the lowest average cost but the highest dependence, lowest inclusion, and most negative autonomy margin. Banks have the lowest dependence and a positive TFAM, although their average cost is highest. Digital Credit Unions and managed hybrid pathways have intermediate costs and relatively strong inclusion and resilience; the hybrid pathway records the highest resilience.

Table 4. Average baseline outputs and TFAM after adaptive packages

Alternative	Cost *C*	Dependence *D*	Inclusion *I*	Resilience *R*	Baseline TFAM	Adaptive TFAM
Bank	0.421	0.348	0.560	0.620	+0.060	+0.157
Independent fintech	0.340	0.588	0.420	0.520	-0.126	-0.003
Platform lending	0.285	0.924	0.200	0.360	-0.440	-0.271
Digital Credit Union	0.327	0.450	0.620	0.620	+0.040	+0.187
Managed hybrid pathway	0.330	0.460	0.600	0.700	+0.040	+0.179

Source: model calculations using calibrated profiles and authors' computational scenario parameters.

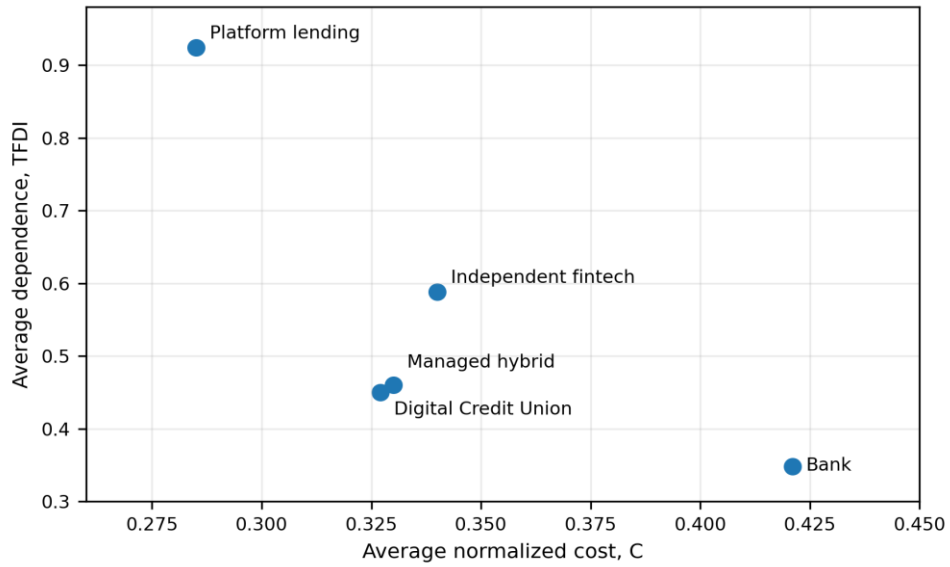


Figure 1. Cost-dependence positions of financing pathways at baseline.
Source: authors' calculations.

Under equal weights, baseline results differ by profile. The managed hybrid pathway has the lowest envelope for h_1; banks lead for h_2 and h_4; banks, Digital Credit Unions, and the hybrid pathway tie for h_3; and banks and the hybrid pathway tie for h_5. These outcomes are conditional scenario results, not a universal institutional ranking.

4.2 Effects of adaptive packages

Average TFAM improves for every alternative. Digital Credit Unions rise from 0.040 to 0.187, managed hybrid pathways from 0.040 to 0.179, banks from 0.060 to 0.157, independent fintech approaches the neutral point, and platform lending remains negative. Improvement across every institutional form confirms that the intervention catalogue was not designed exclusively for one type. Differences reflect baseline conditions, active dependence sources, and assumed readiness.

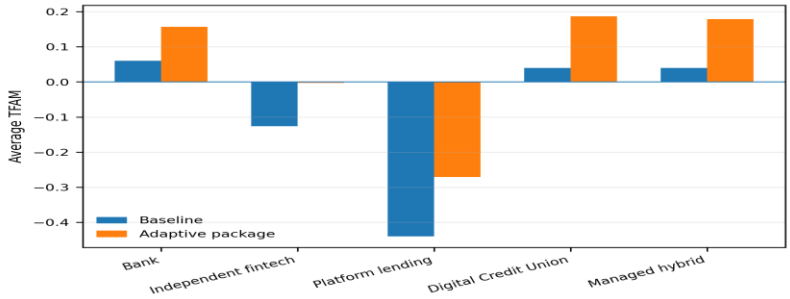


Figure 2. Average autonomy margins before and after adaptive packages.
Source: authors' calculations.

Table 5. Equal-weight selections before and after adaptive packages

Profile	Baseline winner	Adaptive winner	Reported package	Adaptive TFAM
h_1	Managed hybrid pathway	Digital Credit Union	$K_6 + K_7 + K_8$	+0.174
h_2	Bank	Digital Credit Union	$K_3 + K_7 + K_8$	+0.196
h_3	Bank, Digital Credit Union, managed hybrid	Managed hybrid pathway	$K_4 + K_5 + K_8$	+0.220
h_4	Bank	Digital Credit Union	$K_3 + K_7 + K_8$	+0.191
h_5	Bank, managed hybrid	Managed hybrid pathway	$K_4 + K_6 + K_8$	+0.208

Source: authors' calculations. Each displayed package is one reporting representative if several equal-weight minimizers tie.

The nonnegative autonomy-margin gains are consistent with Proposition 2: every retained package satisfies the no-harm inequalities, so autonomy capacity cannot decrease. This is an internal guarantee of the screening rule, not evidence that implementation is costless or equally effective in real institutions.

4.3 Stability across weights and thresholds

Table 6. Frequency of selection across 286 post-intervention policy-weight vectors (%)

Profile	Bank	Digital Credit Union	Managed hybrid
h_1	20.6	45.5	33.9
h_2	0.0	78.0	22.0
h_3	0.0	25.9	74.1
h_4	22.0	57.7	20.3
h_5	23.8	67.5	8.7

Source: authors' calculations; independent fintech and platform lending receive 0% on the tested weight grid.

Digital Credit Unions are most frequently selected for h_1, h_2, h_4, and h_5, while the hybrid pathway is most frequent for h_3. Banks retain nonzero choice regions for h_1, h_4, and h_5. The equal-weight winner is not always the most robust across the full grid: for h_5, the hybrid pathway wins at equal weights, but Digital Credit Unions occupy the larger tested preference region. Corollary 1 explains how the winner can change while each pathway's score remains continuous. Frequencies describe internal stability across a discrete grid, not empirical market probabilities.

Across the 81 threshold combinations, banks, Digital Credit Unions, and managed hybrid pathways remain feasible for all five profiles after intervention. Independent fintech feasibility ranges from 44.4% to 100%, depending on the profile. Platform lending is infeasible under all tested combinations because dependence or inclusion remains outside the tested thresholds. These results do not establish general institutional inferiority; they describe the selected scenarios and three-intervention limit.

4.4 Economic, managerial, policy, and human-dignity implications

Financing evaluation should distinguish contractual price from institutional exposure. A fast and inexpensive pathway may generate long-term dependence costs, while a stable pathway may impose higher process burdens. Decision makers should therefore consider cost, TFDI, inclusion, resilience, and TFAM jointly rather than selecting a pathway from one indicator.

Recommendations should be profile-specific. Rural producers require documentation, raw-material, and logistics support; marketplace traders require reputation portability, algorithmic transparency, and alternative payment channels; manufacturers require working-capital continuity and interoperability; digital firms require alternative data and vendor substitutability; community suppliers require coordination and distribution networks. Uniform programs risk overlooking binding constraints.

Interventions should be interpreted as capabilities available to multiple institutions. Data portability is not platform-specific, and shared infrastructure is not exclusive to cooperatives. Banks can partner with fintech providers, Credit Unions can use modular vendors, and platforms can improve contestability through portability and multi-homing. Symmetry in nominal model treatment does not imply equal implementation costs, regulatory feasibility, or organizational difficulty.

Human dignity cannot be reduced to one score. Its relevance emerges through economic agency: MSMEs should understand data use, have meaningful appeal mechanisms, be able to transfer reputation, choose among providers, and exit without losing business continuity. Consistent with the capability approach, digitalization is inclusive when it expands substantive choices rather than merely increasing transaction volume (Sen, 1999). Lower lock-in is therefore both an efficiency objective and a condition for informed consent, voice, and contestability.

5. Research Limitations and Future Directions

The profiles and financing-need ranges are calibrated from official sources, but the study does not use complete records for five observed individual firms. Detailed cost, dependence, inclusion, resilience, readiness, and intervention-impact parameters remain computational scenarios. Results should not be used to rate particular institutions or estimate behavior for all Indonesian MSMEs.

Symmetric dimensions and nominal intervention intensity reduce design bias but do not ensure equal implementation costs, regulatory constraints, or organizational capability. The 286 weight vectors and 81 threshold combinations demonstrate internal sensitivity, not external validation. The model omits default probability, provider profitability, over-indebtedness, cybersecurity, compliance, and temporal dynamics. Full numerical replication also requires

publication of the complete matrices ρ_{hak}, u_k, Δ_k, source components, fixed normalization anchors, and computational code.

Future research should recalibrate parameters using detailed BISAID records, MSME surveys, provider interviews, expert elicitation, implementation costs, and before-and-after pilots. It should also estimate interaction effects among interventions, integrate uncertainty distributions, include dynamic transition costs, and test whether model-recommended packages improve observed autonomy and business continuity.

6. Conclusion

The tropical multi-semiring framework evaluates MSME digital-financing pathways while preserving the logic of each dimension. Cost is treated as an accumulated burden subject to minimum route selection, dependence as a critical maximum source, and inclusion and resilience as weakest links. A common burden order, feasibility and Pareto screening, and a weighted Chebyshev envelope then compare alternatives without concealing one weakness behind an average.

The research questions yield connected answers. First, the pathways exhibit distinct trade-offs: platform lending has the lowest baseline cost, banks the lowest dependence, and the managed hybrid pathway the highest resilience. Second, adaptive three-intervention packages applied under no-harm screening improve the autonomy margin of every alternative, although gains differ with profiles and readiness. Third, no universal winner emerges. Digital Credit Unions are most robust for four profiles in the weight audit, the hybrid pathway for manufacturing, and banks retain choice regions for several profiles.

Mathematically, route duplication does not alter min-plus selection; autonomy indices have explicit bounds; no-harm packages cannot worsen the burden envelope or TFAM; Pareto filtering is consistent with nonnegative weights; a selected alternative exists for every finite nonempty feasible set; and the envelope is Lipschitz-stable and piecewise linear in policy weights. These guarantees strengthen transparency and replicability but do not replace field calibration, regulatory analysis, or external validation.

The practical contribution is a transparent audit procedure: classify data status, calculate dimension-specific indicators, inspect critical sources and weakest links, screen feasibility, test dominance, apply symmetric no-harm capabilities, and conduct independent weight and threshold audits. Before operational policy or provider selection, the scenario parameters must be calibrated with field data, implementation costs, and regulatory constraints.

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