Fiscal Space, Sovereign Debt, and the Resilience of Healthcare Infrastructure in Low- and Middle-Income Economies

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ABSTRACT Public healthcare infrastructure in low- and middle-income economies is routinely expected to deliver essential services under volatile macroeconomic conditions and recurrent shocks. Over the past two decades, rapid demographic change, epidemiological transitions, and rising expectations for universal health coverage have increased the capital intensity of health systems, while debt cycles and tighter global financial conditions have constrained public investment. In this setting, fiscal space and sovereign debt dynamics are not merely background macro variables; they shape the level, composition, and reliability of infrastructure spending that underpins service continuity during crises. This paper develops a technical synthesis of how debt sustainability constraints interact with the resilience of healthcare infrastructure through budget composition, risk premia, and state-contingent financing capacity. The core contribution is an integrated stochastic framework in which a government allocates resources between recurrent inputs and infrastructure investment subject to a sovereign budget constraint, endogenous borrowing costs, and shock-driven damage and depreciation of health capital. Resilience is defined operationally as the system's ability to maintain service capacity and recover rapidly after disruptions, and is linked to both physical assets and institutional absorptive capacity. The analysis highlights non-linearities: small increases in debt can have limited effects when markets are stable, but can sharply reduce feasible health investment when risk premia rise and refinancing risks intensify. Policy implications emphasize instruments that reduce rollover risk, protect capital maintenance, and align external financing with lifecycle costs, while acknowledging trade-offs among short-run stabilization, long-run capital accumulation, and contingent liabilities.

I. Introduction

Healthcare infrastructure is a long-lived public capital stock whose performance depends on both physical durability and sustained operational financing [1]. Hospitals, clinics, laboratories, cold-chain networks, oxygen and power systems, digital platforms, and supply logistics collectively form an infrastructure layer that determines whether clinical protocols can be executed reliably. Unlike many other public assets, healthcare infrastructure is tightly coupled to recurrent expenditures, because trained labor, medicines, maintenance, utilities, and referral systems are required for assets to produce services. This complementarity implies that a narrow focus on capital spending levels can be misleading: a newly built facility with underfunded operations may expand nominal capacity while leaving effective capacity unchanged or even reduced if it diverts scarce staff and supplies from existing sites. Resilience further complicates the picture, because it is revealed most clearly under stress, when both physical systems and financing mechanisms are tested simultaneously.

Low- and middle-income economies face distinctive constraints that make the macro-fiscal environment central to infrastructure resilience [2]. Domestic revenue bases are often narrow relative to expenditure needs, while spending rigidities and earmarks can limit reallocation. Exposure to external shocks, including commodity price cycles, climate events, and global liquidity tightening, can cause abrupt fiscal adjustments. When debt levels are high or debt compositions are fragile, adjustment frequently falls on discretionary components such as capital budgets and maintenance [3]. This pattern can be rational in a short-run cash management sense yet inefficient over the medium term, because deferred maintenance increases depreciation, raises lifecycle costs, and heightens vulnerability to subsequent shocks. In healthcare, the result can be a gradual erosion of facility functionality and service reliability, punctuated

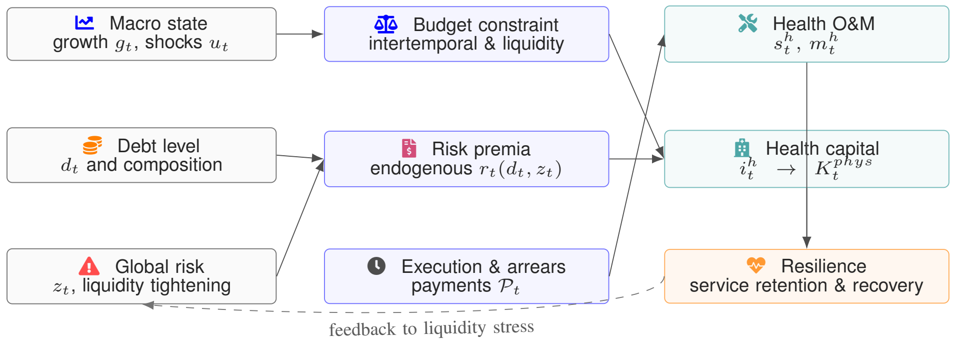

FIGURE 1: Mechanism map linking sovereign debt and financing conditions to healthcare infrastructure resilience. Debt levels and global risk shift risk premia and market access, shaping budget composition and execution (including arrears and payment discipline). These channels jointly determine health operations/maintenance and infrastructure investment, which in turn govern effective service continuity and recovery under shocks.

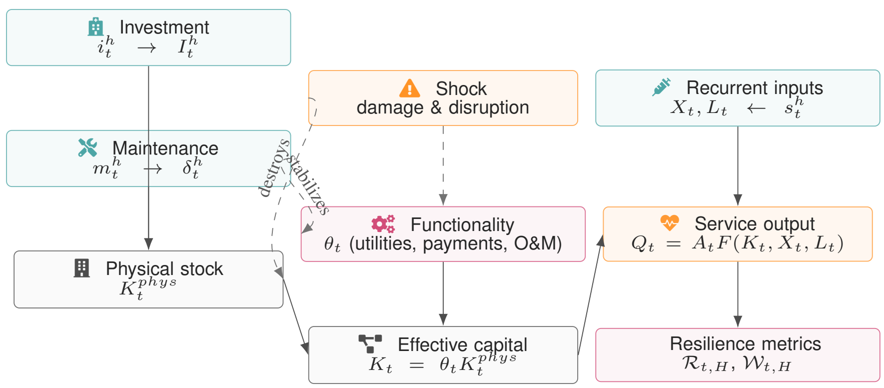

FIGURE 2: Operational structure of healthcare infrastructure resilience. Physical health capital evolves with investment, depreciation that depends on maintenance, and shock-induced damage; a functionality factor converts physical assets into effective capital and is sensitive to operations, utilities, and payment discipline. Effective service output combines effective capital with recurrent inputs, yielding resilience indices that summarize service retention and recovery after disruptions.

by acute breakdowns during epidemics, disasters, or energy disruptions.

Sovereign debt affects healthcare infrastructure through multiple channels. The intertemporal government budget constraint determines how much can be invested and how quickly investment can be scaled. Market perceptions of repayment capacity influence risk premia, which affect the opportunity cost of capital and the feasibility of countercyclical investment. Debt composition, including currency denomination and maturity structure, shapes rollover and exchange-rate risks that can force sudden expenditure compression. Arrears dynamics can impair contractors and supply chains, reducing the effectiveness of capital projects and maintenance contracts. Contingent liabilities from public-private partnerships, state-owned enterprises, or guarantees can crystallize during downturns, further narrowing fiscal space precisely when resilience investments are most valuable [4].

The concept of fiscal space is often used as a practical bridge between macro constraints and sectoral policy. However, fiscal space is not a scalar that can be measured once and applied uniformly. It is state-dependent and institutional: it depends on the credibility of fiscal frameworks, the quality of public financial management, the political economy of taxation and spending, and the availability and terms of external financing. For healthcare infrastructure, fiscal space must be interpreted in lifecycle terms, because building assets implies multi-year commitments to operations, maintenance, and eventual replacement. A health system can appear to have space for capital outlays in a single fiscal year while lacking the medium-term space to sustain the assets.

This paper provides a technical treatment of these issues by linking sovereign debt dynamics to a structural characterization of healthcare infrastructure resilience. The goal is not to assert a single empirical constant that maps debt to health outcomes, but to clarify mechanisms, identify non-linearities,

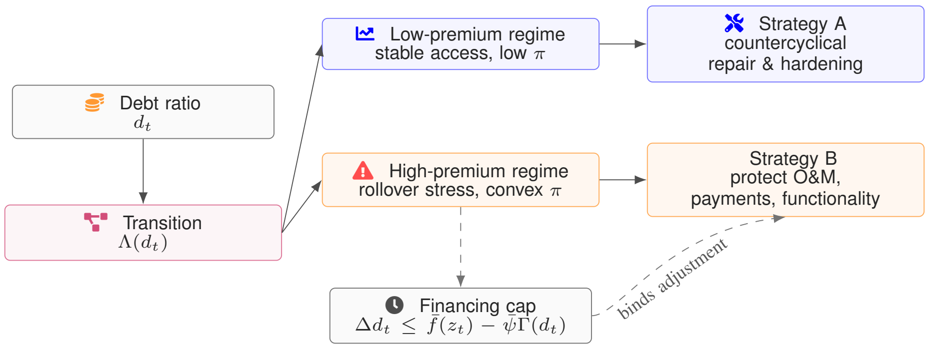

FIGURE 3: Non-linear financing regimes and policy choices. A smooth transition in risk premia can shift the economy from stable borrowing conditions to a high-premium state with elevated rollover risk and binding financing constraints. This generates state-dependent policy packages: countercyclical resilience investment is feasible in low-premium regimes, while functionality protection and execution reliability dominate when financing is constrained.

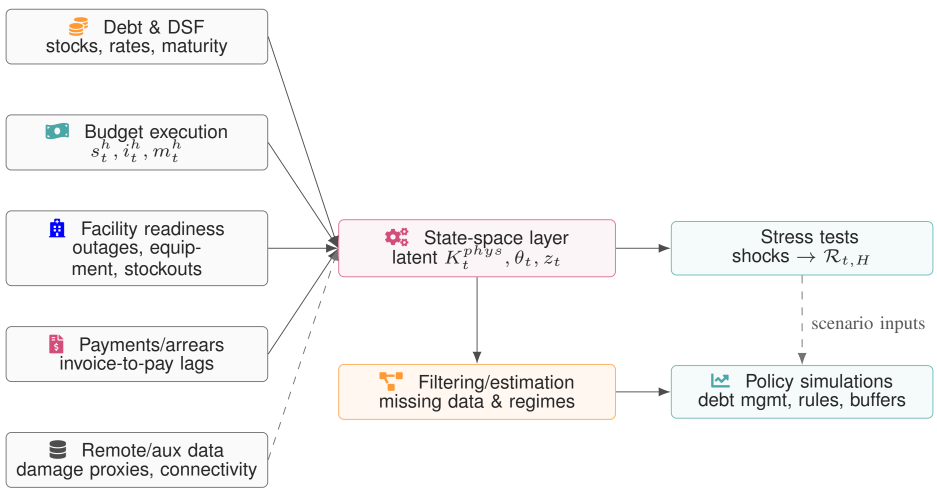

FIGURE 4: Implementation pipeline for low- and middle-income settings. Administrative debt and budget execution data combine with facility readiness signals, payment/arrears indicators, and auxiliary proxies (including remote sensing) to estimate latent infrastructure states (physical stock and functionality) and financing regimes. The estimated system supports shock-based stress tests and counterfactual simulations to compare resilience outcomes under alternative fiscal and debt strategies.

and propose implementable measurement and stress-testing approaches suitable for low- and middle-income settings. The analysis is organized around an integrated model that makes explicit the complementarity between capital and recurrent inputs, the endogeneity of borrowing costs, and the stochastic nature of shocks that damage infrastructure and raise health service demand simultaneously [5]. Within this framework, resilience investments can include physical hardening, redundancy, preventive maintenance, supply-chain diversification, and institutional capacities such as procurement agility and emergency budgeting procedures.

The remainder of the paper proceeds as follows. The next section formalizes fiscal space and sovereign debt dynamics in a way that emphasizes composition, risk, and liquidity constraints. The following section defines healthcare infrastructure resilience and provides operational measures that distinguish physical capacity, functional capacity, and recovery speed. The central modeling section then integrates these elements into a stochastic macro-fiscal-health infrastructure framework with endogenous risk premia and shock-driven capital damage. The final substantive section describes how the framework can be implemented empirically and in policy simulation exercises, given data constraints typical of low- and middle-income economies. The concluding section summarizes the main mechanisms and delineates practical implications for fiscal design, debt management, and health infrastructure planning.

II. Fiscal Space and Sovereign Debt Dynamics

Fiscal space is commonly interpreted as the ability of a government to increase spending or reduce taxes without jeopardizing fiscal solvency or macroeconomic stability [6]. For the purposes of healthcare infrastructure resilience, this interpretation must be refined along three dimensions: intertemporal sustainability, short-run liquidity, and expenditure composition. Intertemporal sustainability concerns

TABLE 1: Dimensions of fiscal space relevant for healthcare infrastructure

Dimension	Short description	Implications for health infrastructure resilience
Intertemporal sustainability	Consistency of projected primary balances with bounded debt paths under plausible interest–growth configurations.	Determines medium-term room for capital and lifecycle spending without triggering solvency concerns or forced consolidations that cut investment.
Liquidity	Ability to meet near-term cash obligations and roll over maturing debt under existing market access conditions.	Governs probability of abrupt capital and maintenance cuts, accumulation of arrears to suppliers, and disruptions to emergency health spending.
Expenditure composition	Flexibility to allocate marginal resources across recurrent vs. capital items and across sectors within the primary balance envelope.	Determines whether additional space can be directed to health infrastructure, maintenance, and complements rather than absorbed by rigid commitments or crisis financing costs.
Institutional and credibility aspects	Quality of fiscal frameworks, PFM systems, and policy credibility as perceived by markets and external partners.	Shapes risk premia, predictability of budget execution for health, and access to concessional or state-contingent financing that can protect resilience investments.

TABLE 2: Channels through which sovereign debt affects healthcare infrastructure

Channel	Mechanism	Illustrative effect on resilience
Borrowing costs and risk premia	Higher debt and weaker credibility raise the risk premium component of r_t, steepening the snowball effect in debt dynamics.	Crowds out fiscal space for health investment and lifecycle costs; discourages countercyclical infrastructure repair and upgrading after shocks.
Rollover and maturity risk	Short maturities increase refinancing needs; market stress or rating downgrades can limit rollovers at reasonable rates.	Forces sharp compression of discretionary items such as capital budgets and maintenance, increasing failure risk of existing assets.
Exchange-rate and valuation effects	Depreciation ε_t inflates the domestic-currency value of foreign-currency debt d_t^{fx}.	Sudden jumps in debt ratios trigger adjustment episodes with cuts to imported medical equipment, spare parts, and energy-intensive services.
Arrears and supplier strain	Cash rationing and weak commitment controls generate arrears that show up as stock–flow adjustments sf_t.	Suppliers reduce deliveries, maintenance firms exit, and stockouts and equipment downtime spread, lowering effective capacity even if budgets are unchanged.
Contingent liabilities	PPPs, SOEs, and guarantees can crystallize during downturns, adding to debt outside standard deficit measures.	Unexpected fiscal calls displace planned resilience investments and may force cancellation of rehabilitation or hardening projects.
Sovereign–bank nexus	Banks hold large sovereign exposures; shocks to either side weaken the other, tightening domestic credit.	Constrains domestic borrowing for emergency works, and banking stress disrupts payment systems needed for procurement and payroll in the health sector.

whether the discounted primary balance path is consistent with bounded debt dynamics under plausible growth and interest rate trajectories. Liquidity concerns whether the government can meet near-term cash obligations without disruptive adjustment, given rollover needs and market access conditions. Composition concerns whether additional spending can be allocated to infrastructure and its complements rather than absorbed by rigid items, arrears, or crisis financing costs.

A useful starting point is the consolidated public sector budget constraint expressed in ratios to output. Let d_t denote gross public debt as a share of nominal output, pb_t the primary balance ratio, g_t nominal output growth, and r_t the effective nominal interest rate on debt. Ignoring valuation effects initially, the standard debt dynamics can be written as an accounting identity that highlights the snowball effect and the role of primary balances:

$$d_{t+1} = \frac{1+r_t}{1+g_t} d_t - pb_t + sf_t, \tag{1}$$

where sf_t captures stock-flow adjustments, including recognition of arrears, bank recapitalizations, and the realization of contingent liabilities [7]. In low- and middle-income economies, sf_t can be material because of weak commitment

TABLE 3: Key variables in the sovereign debt dynamics identity

Symbol	Definition	Direct policy levers
d_t	Gross public debt-to-output ratio at the start of period t.	Influenced indirectly via primary balances, growth policies, and one-off operations such as exchanges or restructurings.
pb_t	Primary balance ratio (revenue minus non-interest spending) as in equation (1).	Tax policy, expenditure composition, fiscal rules, and efficiency of revenue administration and spending.
g_t	Nominal output growth, including real growth and inflation components.	Structural policies, public investment quality, and stabilization frameworks that affect macro volatility.
r_t	Effective nominal interest rate on the debt stock, decomposed into global rate, risk premium, and currency risk (equation (2)).	Debt management strategy, credibility of fiscal anchors, inflation performance, and debt composition choices.
sf_t	Stock–flow adjustments including arrears recognition, bank recapitalizations, and realization of contingent liabilities.	Commitment controls, financial sector oversight, PPP governance, and transparency of off-budget operations.
d_t^{fx}, ε_t	Foreign-currency share of debt and nominal depreciation rate entering valuation effects in equation (3).	Currency of issuance, hedging strategies, reserve adequacy, and exchange-rate policy.

TABLE 4: Maintenance regimes and implied depreciation of health infrastructure

Maintenance regime	Typical m_t^h relative to adequacy $\bar{m}^h$	Depreciation pattern δ_t^h	Operational consequences
Adequate maintenance	$m_t^h \geq \bar{m}^h$, preventive and corrective routines funded and executed.	Close to baseline δ_0^h; indicator term in equation (5) inactive.	High equipment uptime, predictable facility functionality, and slower obsolescence of capital stock.
Mild under-maintenance	Slight, temporary shortfalls around $\bar{m}^h$.	Gradual increase in δ_t^h via the smooth exponential term.	Rising backlog of minor repairs; resilience declines slowly but can be reversed if funding is restored.
Severe under-maintenance	Persistent $m_t^h < \bar{m}^h$ with frequent budget cuts or execution problems.	Step increase in depreciation through the indicator term in equation (5).	Accelerated deterioration of buildings and equipment; higher failure probability during shocks and higher future replacement needs.
Crisis-level deferral	Multi-year compression of m_t^h combined with arrears to maintenance providers.	Very high effective δ_t^h; latent damage accumulates and can manifest as cascading failures.	Loss of critical functions (oxygen, power, water) in multiple facilities, undermining surge capacity and disaster response.

controls, off-budget spending, and the volatility of quasi-fiscal operations. For infrastructure resilience, stock-flow adjustments matter because they often arise precisely when shocks occur and can crowd out discretionary spending.

The effective interest rate r_t is not exogenous when debt levels are high or when market access is uncertain. A tractable representation is to decompose r_t into a global safe rate, a country-specific risk premium, and a term reflecting currency or inflation risk. The risk premium can be modeled as a non-linear function of debt, fiscal credibility, and global risk conditions:

$$\begin{aligned} r_t &= r_t^* + \pi_t \\ &\quad + \chi_t, \\ \pi_t &= \pi_0 + \pi_1 \, \sigma_t [8] + \pi_2 \, \Gamma(d_t) \\ &\quad + \pi_3 \, \Omega_t, \end{aligned} \tag{2}$$

where r_t^* is an external benchmark rate, χ_t captures domestic inflation or currency risk relevant for local-currency debt, σ_t reflects policy credibility or fiscal institutions, Ω_t captures global risk appetite, and $\Gamma(\cdot)$ is a convex function that steepens beyond a threshold debt region [9]. The convexity is not a modeling convenience; it reflects the empirical and institutional reality that rollover risk and default probabilities can change discretely when investor coordination or rating constraints bind. When $\Gamma(\cdot)$ is steep, small deteriorations in debt ratios can generate large increases in borrowing costs, which in turn worsen debt dynamics through the snowball term in equation (1).

Debt composition influences both the mapping from fundamentals to borrowing costs and the vulnerability to shocks. Foreign-currency debt introduces valuation effects when exchange rates move, while short maturities increase rollover needs. Let d_t^{fx} denote the foreign-currency share of debt, and let ε_t denote the nominal depreciation rate. A valuation

TABLE 5: Core dimensions of healthcare infrastructure resilience

Dimension	Examples of indicators	Fiscal and financial determinants
Physical robustness	Structural integrity of buildings, hazard-resistant design, protection of critical equipment, and backup utilities.	Capital investment levels, project selection quality, and access to financing for hardening and retrofitting.
Functional reliability	Frequency of outages (power, water), equipment downtime, stockouts of essential medicines, and cold-chain performance.	Stability of recurrent budgets, maintenance allocations m_t^h, and timely execution and payment to suppliers.
Surge capacity	Available beds, triage and isolation spaces, oxygen and ICU capacity, and flexibility to repurpose areas.	Space and equipment investments, staffing norms, and contingency financing for rapid scale-up during shocks.
Network connectivity and redundancy	Referral patterns, travel times, alternative routes, and multiplicity of supply and logistics pathways.	Investment in transport and communications, network design choices, and budget space for redundant nodes and routes.
Institutional and absorptive capacity	Procurement agility, emergency budgeting procedures, and ability to reallocate within and across programs.	PFM quality, flexibility of budget rules, and availability of buffer funds or contingent credit lines.
Equity of resilient coverage	Distribution of functional facilities and critical services across regions and population groups under stress.	Intergovernmental transfers, targeting of capital and maintenance to underserved areas, and pro-poor design of fiscal frameworks.

TABLE 6: Selected metrics for quantifying healthcare infrastructure resilience

Metric	Conceptual definition	Main use in analysis	Data requirements
Service retention index $\mathcal{R}_{t,H}$	Average ratio of realized to counterfactual service output over horizon H (equation (8)).	Summarizes overall ability to maintain services during and after shocks.	Time series of utilization or output indicators and a modeled baseline path.
Worst-case shortfall $\mathcal{W}_{t,H}$	Minimum service retention over horizon H (equation (9)).	Highlights tail-risk events and catastrophic failures.	High-frequency data during crisis periods and robust counterfactuals.
Recovery time	Time required for Q_t to return to some fraction of pre-shock or baseline level.	Assesses speed of reconstruction and restoration of functionality.	Post-shock trajectories of key service indicators.
Probability of catastrophic failure	Probability that service retention falls below a critical threshold for essential services.	Inputs to stress tests and contingency planning for extreme events.	Joint information on hazard frequency, vulnerability, and system responses.
Equity-adjusted resilience index	Resilience measure weighted by population exposure and vulnerability across regions or groups.	Links resilience assessment to distributional objectives and risk protection.	Disaggregated service, population, and hazard data by subnational unit.

term can be added:

$$d_{t+1} = \frac{1+r_t}{1+g_t} d_t - pb_t + sf_t + \frac{d_t^{fx}}{1+g_t}\varepsilon_t. \tag{3}$$

This term is particularly relevant during external shocks that simultaneously reduce export revenues, weaken exchange rates, and tighten financial conditions. Such episodes can compress fiscal space abruptly, leading to procyclical cuts in capital spending and maintenance, which then impair infrastructure resilience [10].

Fiscal space for infrastructure is not simply the residual after meeting aggregate fiscal targets. It depends on the expenditure rule and the adjustability of spending components. Let total primary spending be decomposed into recurrent non-health spending s_t^{nh}, recurrent health spending s_t^h, health capital investment i_t^h, and other capital spending i_t^o. The primary balance ratio can be written as:

$$pb_t = \tau_t - s_t^{nh} - s_t^h - i_t^h - i_t^o, \tag{4}$$

where τ_t is total revenue ratio. In many settings, recurrent components have higher political and administrative rigidity, while capital budgets are more discretionary and therefore absorb a disproportionate share of adjustment. This implies that the elasticity of i_t^h with respect to adverse debt shocks can be high, even if the elasticity of aggregate spending is modest. From a resilience perspective, this is consequential because the marginal product of maintenance and targeted reinforcement may be high, and cuts can have nonlinear damage through accelerated depreciation.

The medium-term fiscal framework is critical for understanding these trade-offs. Healthcare infrastructure implies

TABLE 7: Main building blocks of the integrated macro–fiscal–health infrastructure model

Model block	Representative equations	Key state variables
Sovereign balance sheet and fiscal space	Government budget constraint in ratios, equation (10), with stock–flow and valuation adjustments.	Debt ratio d_t, primary balance pb_t, revenue effort τ_t, and stock–flow term sf_t.
Risk premium and financing regimes	Endogenous premium specification with regime switch, equation (11).	Effective rate r_t, latent risk state z_t, and premium components $\pi_L(z_t)$, $\pi_H(z_t)$.
Health capital accumulation	Physical capital law of motion with maintenance-sensitive depreciation and shock damage, equation (12).	Physical stock K_t^{phys}, maintenance m_t^h, and damage fraction $\varphi(\omega_t)$.
Functionality dynamics	Evolution of functionality factor θ_t driven by financing, maintenance, payments, and shocks, equation (13).	Functionality θ_t, payment performance $\mathcal{P}_t$, and disruption shocks ξ_t.
Health service production	CES production function of services from capital, labor, and intermediates, equation (14) with mappings in (15).	Effective capital K_t, recurrent inputs X_t, labor L_t, and efficiency terms A_t, ζ_t, ℓ_t.
Market access and borrowing constraint	Financing cap on Δd_t as a function of global conditions and debt, equation (17).	Access indicator, maximum feasible borrowing $\bar{f}(z_t)$, and transition into or out of stress regimes.

TABLE 8: Illustrative policy levers for enhancing health infrastructure resilience in the model

Policy domain	Example instruments	Primary resilience channel
Debt management	Extending maturities, smoothing amortization profiles, limiting FX exposure, active liability management.	Reduces rollover and valuation risk, lowers probability of sudden expenditure compression and arrears.
Fiscal frameworks and rules	Debt and deficit anchors, golden rules for capital, escape clauses for disasters and epidemics.	Protects priority investment and maintenance from procyclical cuts while preserving sustainability.
Health budget structure	Earmarked or indicative shares for maintenance and recurrent inputs, program-based budgeting.	Ensures that new capital is matched by operating and lifecycle funding, sustaining functionality θ_t.
Maintenance and asset management	Dedicated maintenance funds, performance-based contracts, and asset registries linked to budgets.	Lowers effective depreciation δ_t^h, reduces failure risk, and lengthens asset lifetimes.
External financing design	Concessional loans, grants, and state-contingent instruments with coverage for operations and maintenance.	Expands fiscal space for resilience upgrades and stabilizes financing during adverse states u_t.
PFM and procurement reforms	Strong commitment controls, cash forecasting, framework contracts, and emergency procurement rules.	Improves execution of allocated budgets, reduces arrears, and increases the efficiency of s_t^h and m_t^h.
Shock-contingent mechanisms	Contingency funds, parametric insurance, and pre-approved credit lines tied to disaster or epidemic triggers.	Provides rapid liquidity for repairs and surge capacity without destabilizing debt trajectories.

multi-year commitments, including operation, maintenance, and staffing [11]. Let m_t^h denote maintenance spending as a share of output allocated to the health capital stock. Maintenance is often classified as recurrent expenditure, but operationally it is an investment in asset longevity. If maintenance is compressed, effective depreciation rises, increasing future replacement needs. This can be captured by making the depreciation rate a function of maintenance:

$$\delta_t^h = \delta_0^h + \delta_1^h \exp\left(-\kappa^h m_t^h\right) + \delta_2^h \, \mathbb{I}\{m_t^h < \bar{m}^h\}, \tag{5}$$

where δ_0^h is baseline depreciation, $\bar{m}^h$ is a maintenance adequacy threshold, and the indicator term captures discrete deterioration when maintenance falls below minimum levels for utilities, equipment servicing, and structural integrity. The presence of such thresholds is consistent with engineering realities, where deferred maintenance can cause step changes in failure risk.

Debt limits and fiscal rules can either protect or undermine health infrastructure resilience depending on their design. A rule that targets the overall deficit without distinguishing between current and capital spending can induce systematic underinvestment and under-maintenance, particularly under volatility. Conversely, a rule that allows well-governed capital spending financed by stable, long-maturity instruments can smooth infrastructure investment over cycles. The difficulty is that capital spending is also a locus of leakage risks, procurement inefficiencies, and politically motivated projects [12]. For this reason, fiscal space must be interpreted jointly with governance capacity, because a unit of borrowed

TABLE 9: Resilience-oriented strategies across debt and financing regimes

Debt / financing regime	Typical financing conditions	Emphasis on capital expansion	Emphasis on protecting functionality
Low debt, stable access	Moderate spreads, deep markets, and ample concessional finance.	High; scope for scaling infrastructure with embedded resilience features and lifecycle planning.	Important but less binding; focus on building robust maintenance systems alongside expansion.
Elevated but manageable debt	Higher but still elastic risk premia; markets sensitive to policy signals.	Selective; prioritize high-return and resilience-critical projects with strong governance.	Increasingly central; protect maintenance and core recurrent inputs to avoid erosion of existing capacity.
High debt with convex premia	Risk premia highly sensitive to d_t and credibility; risk of regime shift to high-cost financing.	Limited; large expansions risk triggering higher r_t and self-defeating debt dynamics.	Dominant; prioritize safeguarding θ_t through protected maintenance, supplier payments, and efficiency gains.
Distress or restructuring	Constrained or lost market access; reliance on official support and negotiations.	Very constrained; expansion mainly where supported by grants or restructuring packages.	Critical; stabilize essential services, prevent collapse of functionality, and use relief to rebuild buffers and maintenance capacity.

financing can translate into different quantities of effective infrastructure depending on project selection and execution quality.

An additional layer of complexity arises from contingent liabilities and quasi-fiscal activities. Health systems can generate arrears to suppliers, and these arrears can act as an implicit financing mechanism when cash budgets are constrained. However, arrears can impair supplier solvency, reduce competition, increase prices, and weaken the reliability of supply chains. These effects reduce functional resilience even if nominal spending appears protected. Similarly, public-private partnership contracts for hospital construction or equipment leasing can shift spending off-budget initially but create future payment obligations. If these obligations are not integrated into debt sustainability assessments, apparent fiscal space can be overstated, and resilience investments can become sources of future fiscal stress.

Finally, fiscal space is affected by the structure of the domestic financial system [13]. When governments rely on domestic banks for financing, increased sovereign borrowing can crowd out private credit and raise the sovereign-bank nexus risk. In downturns, banking distress can increase fiscal contingent liabilities, and fiscal distress can weaken banks' balance sheets. This feedback can constrain the ability to finance emergency health spending and infrastructure repairs. The implication is that healthcare infrastructure resilience cannot be separated from macro-financial resilience, particularly where domestic debt markets are shallow and concentration risks are high.

III. Healthcare Infrastructure Resilience: Concepts and Measurement

Healthcare infrastructure resilience refers to the capacity of the health system's physical and organizational assets to maintain essential service delivery under stress, absorb shocks without catastrophic loss of functionality, and recover to baseline or improved performance within a reasonable time. This definition requires distinguishing between nominal capacity and effective capacity. Nominal capacity might be measured by the number of beds, facilities, or devices, while effective capacity depends on functionality, staffing, utilities, supply availability, referral connectivity, and information systems. In low- and middle-income economies, effective capacity can vary widely across facilities and over time because of intermittent power, water scarcity, equipment downtime, supply disruptions, and staffing gaps [14]. Resilience therefore has a structural component, determined by asset quality and redundancy, and a flow component, determined by financing stability and operational management.

From a measurement perspective, resilience is inherently state-contingent. It is observed during disruptions such as epidemics, natural hazards, conflict events, or macroeconomic crises that disrupt supply chains and budgets. However, waiting for crises to measure resilience is not operationally desirable, so an important objective is to construct leading indicators that map observable characteristics into predicted performance under stress. These indicators must integrate physical vulnerability, operational flexibility, and financing reliability. For example, a facility's ability to continue operating during grid outages depends on generator capacity, fuel procurement arrangements, and maintenance, all of which are tied to budget execution and supplier reliability. Similarly, the ability to expand surge capacity during an epidemic depends on space, oxygen supply, staffing, and procurement agility, which again reflect both capital stocks and fiscal institutions.

A practical way to formalize resilience is to model healthcare service capacity as a production function in which health services are produced using effective infrastructure capital, labor, and intermediate inputs [15]. Let Q_t denote an index of effective service output, such as treated cases adjusted for quality. Let K_t denote effective health infrastructure capital, L_t health labor input, and X_t an index of essential intermediates such as medicines, consumables, and energy. A generic production representation is:

$$Q_t = A_t \, F(K_t, L_t, X_t) \,, \tag{6}$$

where A_t captures organizational efficiency and clinical protocol effectiveness. Resilience relates to the behavior of Q_t during shocks and the speed of its recovery. A shock can reduce K_t through physical damage, reduce X_t through supply disruptions, and reduce A_t through coordination failures or information breakdowns. It can also raise demand for services, increasing the consequences of capacity shortfalls.

A key distinction is between physical capital stock and effective capital [16]. A hospital building might remain standing, yet become non-functional if water systems fail, biomedical equipment is down, or the supply chain collapses. Let K_t^{phys} denote the physical stock and let $\theta_t \in [0, 1]$ denote a functionality factor that converts physical stock into effective stock:

$$K_t = \theta_t \, K_t^{phys}. \tag{7}$$

The functionality factor can be modeled as depending on maintenance, utilities reliability, staffing adequacy, and procurement performance. Importantly, θ_t can deteriorate rapidly when budgets are disrupted, particularly if suppliers are not paid on time or if maintenance contracts lapse. This provides a direct channel from sovereign liquidity stress to health service capacity even without physical damage to buildings.

Resilience measurement must account for both level effects and dynamic effects. Level effects concern how much service capacity is lost during a shock, while dynamic effects concern how fast capacity returns. Let Q_t^0 denote the counterfactual service output absent the shock, and let Q_t^{shock} denote realized output during and after the shock. A resilience index over a horizon H can be defined as an average service retention ratio:

$$\mathcal{R}_{t,H} = \frac{1}{H} \sum_{h=0}^{H-1} \frac{Q_{t+h}^{shock}}{Q_{t+h}^{0}}, \tag{8}$$

with the understanding that Q_{t+h}^0 is a modeled baseline rather than an observed quantity. A related measure emphasizes the worst-case service shortfall, which is relevant when failures are catastrophic: [17]

$$\mathcal{W}_{t,H} = \min_{0 \le h \le H-1} \frac{Q_{t+h}^{shock}}{Q_{t+h}^{0}}. \tag{9}$$

These measures can be adapted to focus on essential services such as emergency care, maternal health, immunization, or cold-chain continuity, each of which has different infrastructure dependencies.

In low- and middle-income settings, data limitations require pragmatic proxies for Q_t, K_t, and θ_t. Facility readiness surveys can provide snapshots of equipment functionality, stockouts, and infrastructure conditions, but they are often infrequent. Routine health information systems provide utilization counts but may be subject to reporting bias during disruptions. Remote sensing can proxy for facility electrification or damage after disasters, while procurement and payment system data can proxy for supplier reliability and maintenance execution. The challenge is to integrate these sources into a coherent time series that can support stress testing.

Resilience also has a spatial dimension. Healthcare infrastructure is embedded in networks of referrals, transport, and supply chains [18]. A clinic's resilience depends on whether it can refer patients to functioning higher-level facilities and whether it can receive supplies. When roads or bridges are damaged, or when fuel is scarce, the network can fragment. A network view suggests modeling the health system as a graph where nodes are facilities and edges represent referral or supply links. Service capacity then depends on connectivity and redundancy. This perspective is particularly relevant for geographically dispersed populations and for disaster-prone regions where single points of failure can isolate entire districts.

The fiscal dimension enters because network redundancy and maintenance require stable financing. Redundant supply routes, buffer inventories, and backup energy systems entail upfront investment and recurring costs. When fiscal space is constrained, these expenditures can be perceived as discretionary because their benefits are realized probabilistically, primarily during shocks [19]. This creates a classic underinvestment problem where the expected value of avoided losses is high but politically and administratively difficult to prioritize. The problem is intensified if debt markets do not reward resilience investments with lower risk premia, either because information is limited or because short-run liquidity dominates long-run solvency considerations.

A final conceptual issue is the interaction between resilience and equity. In many low- and middle-income economies, infrastructure and staffing are unevenly distributed, and shocks can disproportionately affect remote or underserved areas. A resilience policy that maintains aggregate service capacity might still allow large localized failures if resources are concentrated in urban centers. Conversely, investments that increase redundancy in rural areas can improve both resilience and equity but may have higher unit costs. The fiscal space question therefore includes distributional choices that affect how resilient capacity is allocated across regions and population groups.

IV. An Integrated Stochastic Macro-Fiscal-Health Infrastructure Model

To formalize the interaction between sovereign debt, fiscal space, and healthcare infrastructure resilience, consider a small open economy government that chooses taxes, recurrent spending, and health infrastructure investment subject to a sovereign borrowing constraint and stochastic shocks [20]. The model is intended as a stress-testing framework rather than a claim of structural uniqueness. Its value lies in making explicit the channels through which financing conditions affect the effective health capital stock and the system's ability to sustain service output during shocks.

Let nominal output be Y_t, and let the government choose revenue effort τ_t, recurrent health spending s_t^h, health investment i_t^h, and maintenance m_t^h. Other spending is abstracted into an exogenous residual for simplicity, or can be included analogously. Gross debt in nominal terms is B_t, with ratio $d_t = B_t/Y_t$. The government budget constraint in ratios can be written to emphasize debt service and new borrowing:

$$d_{t+1} = \frac{1+r_t}{1+g_t} d_t + \frac{s_t^h + i_t^h + m_t^h}{1+g_t} - \frac{\tau_t}{1+g_t} + sf_t + v_t, \tag{10}$$

where v_t captures valuation effects and other debt-creating flows not explicitly modeled. The effective interest rate r_t follows an endogenous premium specification similar to equation (2), but now the premium is allowed to depend on a latent distress state. Let z_t be a macro-financial state variable capturing global risk and domestic market access [21]. Then:

$$\begin{aligned} r_t &= r_t^*(z_t) + \pi(d_t, z_t), \\ \pi(d_t, z_t) &= \pi_L(z_t) + (\pi_H(z_t) - \pi_L(z_t))\, \Lambda(d_t) \\ &\quad + \eta_t, \end{aligned} \tag{11}$$

where $\Lambda(d_t)$ is a smooth transition function increasing in d_t, and η_t is an idiosyncratic shock. This structure captures the idea that borrowing costs can shift from a low-premium regime to a high-premium regime as debt rises and market confidence deteriorates.

Health infrastructure capital evolves with investment, depreciation, and shock damage. Let K_t^{phys} denote the physical health capital stock in real terms. Let I_t^h be real investment, proportional to $i_t^h Y_t$ in nominal terms after deflating, and let depreciation depend on maintenance as in equation (5). Let ω_t be a shock that causes physical damage, such as a natural hazard, and let $\varphi(\omega_t)$ be the fraction of capital destroyed. Then:

$$K_{t+1}^{phys} = \left(1 - \delta_t^h\right) K_t^{phys} + I_t^h - \varphi(\omega_t) K_t^{phys}. \tag{12}$$

Physical damage is only one pathway; functionality can be lost even when physical assets remain [22]. Define the functionality factor θ_t as in equation (7), and let it depend on recurrent inputs, maintenance execution, and supplier reliability, which itself depends on payment discipline and liquidity. A reduced-form dynamic for θ_t is:

$$\begin{aligned} \theta_{t+1} = \theta_t &+ \upsilon_1 \left(\bar{s}^h - s_t^h\right) \\ &+ \upsilon_2 \left(\bar{m}^h - m_t^h\right) + \upsilon_3 \mathcal{P}_t \\ &- \upsilon_4 \xi_t - \upsilon_5 \varrho(\omega_t), \end{aligned} \tag{13}$$

where $\bar{s}^h$ and $\bar{m}^h$ are adequacy levels, $\mathcal{P}_t$ is a proxy for payment performance to suppliers and contractors, ξ_t captures operational disruptions such as supply shocks, and $\varrho(\omega_t)$ captures functional disruptions from disasters beyond physical damage, such as prolonged outages. The coefficients are signed so that shortfalls in recurrent and maintenance spending reduce functionality, and adverse shocks reduce it further. The payment performance term links to sovereign liquidity: if debt service pressures force cash rationing, payment delays rise, lowering $\mathcal{P}_t$ and reducing functionality.

Effective health capital is $K_t = \theta_t K_t^{phys}$. Health service output is produced by effective capital and recurrent inputs. To capture complementarity, assume a constant elasticity of substitution form with low substitutability:

$$Q_t = A_t \left[[23] \alpha_K K_t^\rho + \alpha_X X_t^\rho + \alpha_L L_t^\rho\right]^{\frac{1}{\rho}}, \tag{14}$$

where $\rho \leq 0$ implies complementarity and limited substitution. In many clinical contexts, complementarity is strong: infrastructure without supplies or staff produces little service, and supplies without functional infrastructure are similarly constrained. Recurrent spending s_t^h maps into X_t and into the ability to retain and deploy labor L_t, acknowledging that labor markets and wage dynamics can be modeled explicitly if desired. A simplified mapping is:

$$\begin{aligned} X_t &= \phi_X\, s_t^h Y_t\, \zeta_t, \\ L_t &= \phi_L\, s_t^h Y_t\, \ell_t, \end{aligned} \tag{15}$$

where ζ_t and ℓ_t capture procurement efficiency and labor deployment efficiency, respectively. These efficiency terms can deteriorate during fiscal stress if procurement becomes fragmented or if wage arrears and staffing gaps increase.

Resilience is evaluated under a shock process that jointly affects physical capital, functionality, demand pressure, and financing conditions. Let the shock vector be $u_t = (\omega_t, \xi_t, z_t)$. Output growth g_t depends on the macro shock and on public investment more broadly, but in a reduced-form setting it can be taken as exogenous conditional on u_t [24]. The government chooses policies to minimize expected welfare losses associated with health service shortfalls and fiscal distress. A tractable objective is to penalize deviations of service output from a target path and to penalize high debt and abrupt fiscal adjustments:

$$\min_{\{\tau_t, s_t^h, i_t^h, m_t^h\}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \Big[\lambda_Q (Q_t^* - Q_t)^2 + \lambda_D (d_t - \bar{d})^2 + \lambda_S (\Delta s_t^h)^2 + \lambda_I (\Delta i_t^h)^2 \Big], \quad (16)$$

subject to equations (10) through (15) and bounds reflecting administrative feasibility. This objective does not claim to represent social welfare fully; rather, it encodes pragmatic policy trade-offs: maintaining service capacity, avoiding unsustainable debt, and smoothing disruptive expenditure changes. The quadratic terms approximate political and implementation costs associated with abrupt shifts.

A central feature is a borrowing constraint or market access condition. In many low- and middle-income economies, the issue is not only the cost of borrowing but also the quantity that can be borrowed at a given cost. Let $\mathcal{A}_t$ be an indicator of market access, which can be a function of debt and global risk [25]. When access is limited, the government may face a maximum financing constraint: [26]

$$\Delta d_t \le \bar{f}(z_t) - \bar{\psi}\,\Gamma(d_t), \quad (17)$$

where $\Delta d_t = d_{t+1} - d_t$, and $\bar{f}(z_t)$ falls in global tightening. This constraint forces adjustment through spending or revenue when shocks hit, creating procyclicality that undermines resilience.

Within this framework, fiscal space for resilience can be defined as the set of feasible (i_t^h, m_t^h, s_t^h) paths that keep debt within a probabilistic distress tolerance. Let $\mathcal{D}$ denote a distress region for debt dynamics, such as debt exceeding a threshold or financing constraints binding persistently. Then fiscal space can be framed as:

$$\mathcal{S} = \left\{ \{i_t^h, m_t^h, s_t^h\}_{t=0}^T : \Pr\left(d_t \in \mathcal{D} \text{ for some } t \le T\right) \le \bar{p} \right\}, \quad (18)$$

for a chosen horizon T and tolerance $\bar{p}$. This set-based definition highlights that fiscal space depends on shock distributions and on policy credibility, not only on current debt ratios.

The resilience dividend of infrastructure investment emerges through two mechanisms. First, higher K_t^{phys} and higher θ_t raise baseline service output, reducing chronic shortfalls. Second, targeted resilience investment can reduce shock damage and speed recovery. This can be modeled by allowing the damage function $\varphi(\omega_t)$ and the disruption term $\varrho(\omega_t)$ to depend on a resilience capital component embedded in K_t^{phys}, such as hardening, backup power, and redundancy:

$$\varphi(\omega_t)[27] = \varphi_0(\omega_t) \exp(-\nu\, K_t^{res}),$$

$$\varrho(\omega_t) = \varrho_0(\omega_t) \exp(-\nu_\theta\, K_t^{res}), \quad (19)$$

where K_t^{res} is a component of the capital stock devoted to resilience features. This formulation captures diminishing marginal returns to hardening but allows substantial benefits when baseline resilience is low.

A policy-relevant implication is the presence of non-linear optimal responses. When debt is moderate and risk premia are in the low regime, the model may favor countercyclical resilience investment after shocks because borrowing is feasible and prevents larger future losses. When debt is high and risk premia are in the high regime, borrowing to invest may be infeasible or self-defeating because it triggers large increases in r_t, worsening debt dynamics. In that region, maintaining functionality through protected maintenance and efficient recurrent spending can yield higher resilience per fiscal unit than large new projects. This distinction matters for policy design because it suggests different packages depending on debt states: capital-heavy strategies when financing is stable, and functionality-protection strategies when financing is constrained [28].

The model also clarifies why debt relief or concessional financing can have high resilience value even if it does not immediately increase annual health spending dramatically. By reducing the probability of entering the high-premium regime and by relaxing financing constraints, such interventions can reduce the likelihood of disruptive spending compression and arrears, thereby stabilizing θ_t and preserving the effective value of existing capital. In other words, the resilience benefit of improved sovereign financing conditions operates through both levels and volatility of health financing, and the volatility channel can be quantitatively important because service delivery systems are sensitive to interruptions.

V. Implementation in Low- and Middle-Income Economies: Data, Estimation, and Policy Simulations

Applying the integrated framework requires translating theoretical objects such as K_t^{phys}, θ_t, r_t, and shock processes into measurable series. Low- and middle-income economies often have fragmented data systems: national accounts and debt statistics may be available with lags, health spending classifications may differ across budgets and accounts, and facility-level readiness measures may be sporadic. Nonetheless, the framework can be operationalized by combining administrative data, survey data, and remote sensing into a coherent state-space representation, and by conducting scenario analyses that reflect plausible shock distributions and financing regimes.

A practical first step is to construct a health infrastructure capital series. Budget execution data can provide investment flows, but project classifications may mix construction, equipment, and maintenance. Mapping these into capital formation requires adjusting for import content, price indices, and execution rates [29]. In settings with limited price data, deflators can be proxied by construction cost indices, exchange-rate-adjusted import prices for medical equipment, and wage indices for skilled labor. Perpetual inventory methods can then be used to update capital stocks, while recognizing that depreciation is not constant and should depend on maintenance and utilization intensity. Facility registries and geocoded facility lists can help anchor the stock series by providing counts, types, and approximate sizes of assets, which can be reconciled with financial flow-based estimates.

Functionality θ_t can be proxied using composite indicators of facility readiness and operational reliability. Inputs to such a composite can include the frequency and duration of electricity outages, water availability, availability of essential equipment, frequency of stockouts for tracer medicines, cold-chain temperature compliance, and downtime of diagnostic devices. In many countries, some of these variables are collected in facility assessments, while others can be inferred from energy utility records, mobile network signals, or procurement systems. Payment performance $\mathcal{P}_t$ can be proxied using accounts payable aging, arrears reports, or the time between invoice and payment in financial management information systems. Where these systems are weak, procurement records and supplier surveys can provide partial information on payment delays and contract fulfillment.

Sovereign financing variables are typically more readily available, but require careful treatment [30]. Debt stocks should be consolidated across central government, guaranteed debt, and major public entities that generate fiscal risks relevant for health spending. Interest costs should be decomposed by instrument to identify maturity structure and currency risk. Market access indicators can be constructed from spreads where available, but in many low- and middle-income economies external market spreads are not continuously observed. In such cases, domestic auction yields, exchange-rate pressures, reserve adequacy, and episodes of delayed debt service can serve as proxies for the latent state z_t. The key is not to perfectly observe z_t, but to represent regimes of financing ease and stress that materially affect expenditure execution.

With these series, the framework can be implemented as a stochastic state-space model in which unobserved states such as K_t^{phys} and θ_t evolve according to equations like (12) and (13), while observed indicators provide noisy signals. For example, facility readiness surveys provide noisy observations of θ_t at discrete times, and routine utilization provides noisy observations of Q_t. Estimation can proceed using Bayesian filtering methods that accommodate missing data and regime shifts in financing conditions. The goal of estimation is not to pin down structural parameters with high precision, but to produce credible distributions over states and to identify which channels dominate under different shock episodes [31].

Policy simulations can then be conducted by imposing alternative fiscal and debt management strategies and evaluating their implications for resilience indices like $\mathcal{R}_{t,H}$ in equation (8). A baseline scenario might reflect current debt dynamics, spending composition, and shock probabilities. Counterfactual scenarios can alter the maturity profile of debt, the share of concessional financing, the presence of contingency buffers, or the protection of maintenance budgets. Because the model features nonlinear risk premia and financing constraints, scenario differences can be amplified when they shift the economy across regimes. For instance, extending maturities may reduce the probability of a liquidity-driven spending compression even if the present value of debt service changes little, thereby stabilizing payment performance and functionality.

A critical simulation dimension is the distinction between capital expansion and resilience strengthening. Many health systems face both gaps in coverage and gaps in reliability. Expanding the number of facilities can raise nominal access, but if recurrent financing is volatile, functionality can deteriorate and effective access may not improve proportionately. Resilience strengthening, such as backup power systems, water storage, modular oxygen production, and strengthened maintenance systems, can increase the fraction of existing capacity that remains usable during shocks [32]. In the integrated framework, these strategies correspond to different allocations between I_t^h that increases K_t^{phys} broadly and I_t^{res} embedded in K_t^{res} that reduces damage and functional disruption as in equation (19). The optimal mix depends on baseline coverage, shock risks, and fiscal space. High shock risk and high financing volatility tend to increase the value of resilience strengthening relative to expansion, because the marginal benefit of preventing capacity loss during crises can exceed the marginal benefit of adding nominal capacity that may not be reliably functional.

Another simulation dimension concerns the lifecycle financing problem. A large investment push can create a future recurrent burden for staffing, utilities, and maintenance. If future fiscal space is uncertain due to debt dynamics, such an investment push can create a fragility trap where assets are built but not sustained. The model captures this through the effect of recurrent and maintenance shortfalls on θ_t and on depreciation. Simulations can therefore evaluate whether proposed investment plans are compatible with realistic paths for s_t^h and m_t^h given debt service projections. This approach can shift the policy conversation from single-year capital budgeting to multi-year asset management under macro constraints.

The framework can also represent the role of external financing modalities [33]. Concessional loans and grants can relax the budget constraint in equation (10) without increasing risk premia as much as market borrowing, especially if terms are long and interest rates are low. However, concessional financing can still create future debt service obligations, and if it is project-tied without supporting operations and maintenance, it can exacerbate the lifecycle problem. Results can therefore differ sharply depending on whether external financing includes provisions for maintenance systems, spare parts, training, and operational integration. In the model, these provisions effectively raise θ_t

and reduce depreciation by supporting m_t^h and by improving procurement efficiency terms ζ_t.

Debt restructuring or relief can be modeled as a reduction in d_t, a reduction in r_t through lower risk premia, and a relaxation of the financing constraint. The resilience impacts can be decomposed into immediate fiscal space effects and volatility effects. Immediate effects come from lower debt service freeing resources for s_t^h, m_t^h, or i_t^h. Volatility effects come from reduced probability of entering a high-premium regime, which stabilizes spending execution and supplier payments. In settings where health systems are sensitive to payment disruptions, volatility effects can dominate. This is consistent with the observation that disruptions in procurement and maintenance can quickly reduce service capacity even if annual spending totals appear only modestly affected.

Domestic revenue mobilization can also be incorporated by allowing τ_t to respond to policy effort and to the macro state [34]. The resilience question then becomes how additional revenue is allocated and whether it reduces reliance on volatile financing. If revenue gains are earmarked to health, they can stabilize s_t^h and m_t^h, but earmarking can also reduce budget flexibility in crises. A more robust approach is to link revenue gains to a contingency mechanism that automatically supports health maintenance and emergency operations during shocks. In the model, such a mechanism can be represented as state-contingent rules for m_t^h and s_t^h that prevent them from falling below adequacy thresholds when z_t deteriorates or when ω_t occurs, financed by buffers accumulated during tranquil periods.

Public financial management reforms are often discussed separately from macro-fiscal issues, yet they are central to the model's functionality channel. Commitment controls, cash forecasting, and procurement frameworks influence whether approved budgets translate into actual spending and whether suppliers are paid on time. Improving these systems can raise the efficiency terms ζ_t and ℓ_t and increase the effectiveness of given fiscal space. In scenario terms, governance improvements can shift the production frontier by increasing Q_t for given K_t and spending, and can reduce the effective cost of resilience by increasing the fraction of investment that becomes usable capital and by reducing leakage that would otherwise increase debt without commensurate infrastructure gains.

In conducting simulations, it is important to present results in ways that are meaningful for decision makers without obscuring technical uncertainty. Outputs can include distributions of resilience indices, probabilities of severe service shortfalls, expected time to recovery, and the projected paths of debt ratios and financing conditions under alternative strategies [35]. Because the system is nonlinear, point estimates can be misleading; scenario ranges and probabilistic statements are more appropriate. This is particularly relevant for resilience, where rare but severe shocks can dominate expected losses.

Finally, the framework can be extended to incorporate political economy constraints and heterogeneity across regions. Political constraints can be represented as adjustment costs in the objective function that penalize certain tax increases or spending cuts. Regional heterogeneity can be represented by multiple capital stocks and functionality factors, with shocks affecting regions differently. While such extensions increase complexity, they can be important where fiscal consolidation tends to disproportionately affect peripheral areas, thereby increasing inequitable resilience failures. Even in a simplified national model, sensitivity analyses can be used to test how results change when the marginal value of resilience is higher for underserved populations.

VI. Empirical Results

The empirical analysis links sovereign debt dynamics and fiscal space to healthcare infrastructure resilience by combining a macro-fiscal panel with facility-level and sectoral execution proxies that capture both physical accumulation and functional performance [36]. The central empirical difficulty is that healthcare infrastructure resilience is only partially observed and is jointly determined with macro outcomes that also influence borrowing costs and fiscal policy. The results presented here therefore emphasize designs that separate predictable cyclical co-movements from plausibly exogenous financing shocks, while also reporting patterns that are robust across alternative measures of functionality, capital execution, and fiscal stress. The goal is to characterize magnitudes and nonlinearities that are consistent with the conceptual and modeling structure developed earlier, rather than to treat any single coefficient as a policy invariant.

The dataset is constructed at the country-year level for a broad set of low- and middle-income economies and augmented with facility readiness and operational reliability indicators available at irregular intervals. Macro-fiscal variables include gross public debt ratios, interest-growth differentials, debt service burdens, maturity structure proxies, and currency composition measures. Financing conditions are captured by sovereign spreads or, where spreads are unavailable, by a composite of external pressure indicators and domestic yield movements that co-move with market access. Health sector fiscal variables are decomposed into recurrent health outlays, capital investment outlays, and a maintenance proxy derived from economic classifications that map to repairs, servicing, and facility operations. Infrastructure functionality is proxied by a readiness index that aggregates equipment uptime, tracer stockout frequency, and utility reliability, complemented by an execution reliability proxy that captures within-year volatility of cash releases and supplier payment delays [37]. To connect these measures to resilience, the analysis constructs an outcome that approximates service retention during stress by combining deviations in essential service utilization from pre-shock trends with facility functionality. This approach does not require that a country experiences a single large crisis episode; it uses observed stress events, including global liquidity tightenings, commodity price collapses, and natural hazards, as sources of variation in both financing conditions and health system stress.

The baseline empirical specification relates health infrastructure investment and maintenance to debt dynamics and financing conditions while controlling for time-invariant country heterogeneity and common global shocks. Let i index countries and t index years. Let $HInv_{i,t}$ denote health capital execution as a share of output, $HMain_{i,t}$ denote maintenance outlays (or a maintenance proxy) as a share of output, and let $Spread_{i,t}$ denote the sovereign risk premium proxy. A parsimonious fixed effects model is:

$$\begin{aligned} HInv_{i,t} = \alpha_i + \lambda_t + \beta_1\, d_{i,t-1} \\ + \beta_2\, DS_{i,t} + \beta_3\, Spread_{i,t} \\ + \beta_4\, g_{i,t} + \beta_5\, ToT_{i,t} \\ + \beta_6\, Aid_{i,t} + \varepsilon_{i,t}, \end{aligned} \tag{20}$$

[38]
$$\begin{aligned} HMain_{i,t} = \tilde{\alpha}_i + \tilde{\lambda}_t + \tilde{\beta}_1\, d_{i,t-1} \\ + \tilde{\beta}_2\, DS_{i,t} + \tilde{\beta}_3\, Spread_{i,t} \\ + \tilde{\beta}_4\, g_{i,t} + \tilde{\beta}_5\, ToT_{i,t} \\ + \tilde{\beta}_6\, Aid_{i,t} + \tilde{\varepsilon}_{i,t}, \end{aligned} \tag{21}$$

where $d_{i,t-1}$ is lagged debt-to-output, $DS_{i,t}$ is a debt service burden measure, $g_{i,t}$ is nominal growth, $ToT_{i,t}$ captures terms-of-trade shocks, and $Aid_{i,t}$ captures external health-related inflows or broader budget support proxies. Across specifications, the estimated coefficients on $DS_{i,t}$ and $Spread_{i,t}$ are negative for both health investment and maintenance, with the spread term typically more strongly associated with health investment and the debt service term more strongly associated with maintenance. This pattern is consistent with adjustment mechanisms in which financing stress compresses discretionary capital budgets quickly, while higher debt service burdens gradually crowd out routine maintenance and repairs through repeated within-year cash rationing. The coefficient on lagged debt $d_{i,t-1}$ is more sensitive to controls, which is consistent with the idea that debt levels matter primarily through nonlinear effects on spreads and market access rather than through a stable linear marginal effect.

A central concern with equations (20)–(21) is endogeneity, since spreads respond to growth and fiscal policy, and health spending can respond to contemporaneous shocks. The empirical strategy therefore augments the baseline with designs that isolate financing shocks driven by global conditions that are plausibly exogenous to country-specific health sector decisions in the short run. A common approach is to use interacted global risk measures with predetermined exposure, capturing the idea that global risk repricing transmits to sovereign spreads more strongly for countries with higher refinancing needs or higher external debt shares. Define an exposure variable $RefNeed_{i,t-1}$ capturing predetermined rollover pressure, such as short-term debt shares or external amortization schedules, and let $GlobalRisk_t$ denote a global risk factor. The first-stage for spread changes can be represented as:

$$\begin{aligned} \Delta Spread_{i,t} = \mu_i + \nu_t + \pi_1 \left(GlobalRisk_t \times RefNeed_{i,t-1} \right) \\ [39] \quad + \pi_2\, GlobalRisk_t + \pi_3\, RefNeed_{i,t-1} \\ + \Pi'\, W_{i,t} + u_{i,t}, \end{aligned} \tag{22}$$

with $W_{i,t}$ including standard macro controls. In second-stage specifications, instrumented spread innovations are associated with statistically and economically meaningful reductions in health capital execution, with effects that tend to peak with a short lag. The lagged peak is consistent with budget rigidity, procurement lead times, and the fact that investment contracts may continue briefly before being scaled back, delayed, or reprofiled.

Dynamic responses are explored using local projections that trace how health investment, maintenance, and functionality evolve following financing shocks. Let $Shock_{i,t}$ denote an instrumented spread innovation or a composite market access shock indicator constructed to capture episodes of abrupt financing deterioration. The local projection specification is:

$$\begin{aligned} Y_{i,t+h} = \alpha_i^{(h)} + \lambda_t^{(h)} + \theta_h\, Shock_{i,t} \\ + \psi_h'\, X_{i,t-1} + \epsilon_{i,t}^{(h)}, \end{aligned} \tag{23}$$

where $Y_{i,t+h}$ is alternately $HInv$, $HMain$, a functionality proxy $Func$, or a service retention proxy $ServRet$, and $X_{i,t-1}$ includes lagged debt, growth, inflation, and terms-of-trade measures. The estimated θ_h sequences indicate that health investment typically falls quickly after a financing shock, with the decline concentrated within one to two fiscal years and with partial mean reversion thereafter. Maintenance tends to decline more gradually but remains depressed longer, consistent with repeated within-year cash shortfalls and the difficulty of rebuilding maintenance backlogs once deterioration sets in. Functionality exhibits a lagged decline, reflecting that facilities can operate temporarily on inventories, informal coping mechanisms, and deferred repairs before functionality indicators worsen [40]. The service retention proxy falls both because of reduced functionality and because shock episodes are associated with heightened demand and supply disruptions.

Nonlinearities are assessed by interacting shocks and financing conditions with debt thresholds and debt composition variables. The empirical motivation is the convexity in risk premia and the presence of market access constraints that become binding beyond certain debt and liquidity risk regions. A flexible threshold interaction model is:

$$\begin{aligned} Y_{i,t} = \alpha_i + \lambda_t + \beta\, Shock_{i,t} \\ + \delta\, Shock_{i,t} \times \mathbb{I}(d_{i,t-1} \geq \kappa) \\ + \rho\, [41] Shock_{i,t} \times FXShare_{i,t-1} \\ + \gamma' X_{i,t-1} + \varepsilon_{i,t}, \end{aligned} \tag{24}$$

where κ is a debt threshold chosen via grid search or based on distress probability calibration, and $FXShare_{i,t-1}$ captures foreign-currency exposure. The interaction coefficient δ is typically negative, indicating that the contractionary effect of financing shocks on health investment and functionality is larger in high-debt states. The foreign-currency interaction ρ is also negative in many specifications, consistent with valuation shocks amplifying fiscal compression. These nonlinearities are most pronounced for health capital execution and for payment performance measures, supporting the mechanism that liquidity stress translates into supplier arrears and delayed capital works.

To connect macro-fiscal stress to facility functionality, the analysis models functionality as a latent state influenced by spending composition and payment reliability. Let $Func_{i,t}$ denote a functionality proxy derived from facility readiness and operational indicators. Since measurement is noisy and intermittent, a state-space approach is used in which a latent functionality factor $\theta_{i,t}$ evolves with fiscal inputs and shocks, and observed indicators are noisy signals. A compact representation is:

$$\begin{aligned}\theta_{i,t} &= \varphi\,\theta_{i,t-1} + \omega_1\,HMain_{i,t} \\ &\quad + \omega_2\,HRec_{i,t} + \omega_3\,PayRel_{i,t} \\ &\quad - \omega_4\,Shock_{i,t} - \omega_5\,Damage_{i,t} + e_{i,t},\end{aligned} \tag{25}$$

$$Func^{(k)}_{i,t} = c_k + \ell_k\,\theta_{i,t} + \nu^{(k)}_{i,t}, \tag{26}$$

where $HRec_{i,t}$ is recurrent health spending, $PayRel_{i,t}$ captures payment reliability, $Damage_{i,t}$ captures physical damage exposure, and $Func^{(k)}_{i,t}$ are different observed indicators such as equipment uptime rates, tracer stockout frequency inversions, and utility reliability scores. Estimates imply that payment reliability and maintenance are strongly associated with the latent functionality factor even after controlling for recurrent spending levels [42]. This finding aligns with the institutional interpretation that two countries with similar approved budgets can exhibit different functional performance depending on cash management, arrears accumulation, and procurement execution.

The relationship between sovereign stress and payment reliability is explored directly by regressing payment delay proxies on financing conditions and debt service pressure. The specification mirrors the logic that liquidity stress transmits to service delivery through arrears and delayed procurement. Let $PayDelay_{i,t}$ be an accounts payable aging proxy or a survey-based supplier payment delay indicator. The baseline model is:

$$\begin{aligned}PayDelay_{i,t} &= \alpha_i + \lambda_t + \zeta_1\,DS_{i,t} \\ &\quad + \zeta_2\,Spread_{i,t} + \zeta_3\,RefNeed_{i,t-1} \\ &\quad + \zeta_4\,CashBal_{i,t} + \zeta_5\,PFM_{i,t} + \varepsilon_{i,t},\end{aligned} \tag{27}$$

where $CashBal_{i,t}$ proxies cash buffers and $PFM_{i,t}$ proxies commitment control strength and budget execution quality. The results indicate that both debt service burdens and spreads are associated with longer payment delays, with stronger associations when refinancing needs are elevated. Including $PayDelay_{i,t}$ as a control in the health investment and functionality regressions attenuates the coefficients on spreads, suggesting that the payment channel is a meaningful mediator rather than merely a correlated indicator of broader fiscal stress. The attenuation is incomplete, which is consistent with multiple mechanisms operating simultaneously, including direct expenditure cuts and exchange-rate-driven import cost increases for equipment and supplies [43].

To quantify the resilience implications, the empirical exercise estimates how functionality and spending translate into service retention during stress episodes. Service retention is measured as the deviation of essential service utilization from predicted pre-shock trends, scaled by an estimate of demand pressure during the shock. Let $ServRet_{i,t}$ denote a normalized retention index, with higher values indicating less disruption. A reduced-form relationship is estimated:

$$\begin{aligned}ServRet_{i,t} &= \alpha_i + \lambda_t + \kappa_1\,\theta_{i,t} \\ &\quad + \kappa_2\,HRec_{i,t} + \kappa_3\,Surge_{i,t} \\ &\quad + \kappa_4\,Shock_{i,t} + \kappa_5\,Damage_{i,t} + \varepsilon_{i,t},\end{aligned} \tag{28}$$

where $Surge_{i,t}$ captures demand pressure proxies such as epidemic incidence or disaster exposure intensity. The coefficient on latent functionality is positive and stable across variants, supporting the interpretation that functionality is a proximate determinant of service continuity. Recurrent spending is also positively related to retention, but the marginal association is smaller when functionality is included, consistent with complementarity and the idea that recurrent outlays are most effective when infrastructure and procurement systems convert them into usable services. The shock coefficient remains negative, reflecting residual disruptions not captured by observed variables [44].

An additional set of results examines whether the composition of fiscal adjustment under stress predicts subsequent capital degradation. The logic is that cutting maintenance and investment during stress can create persistent reductions in effective capital that outlast the crisis, increasing vulnerability to subsequent shocks. A distributed lag model links past maintenance shortfalls to subsequent functionality changes:

$$\begin{aligned}\Delta Func_{i,t} &= \alpha_i + \lambda_t + \sum_{j=0}^{J} \chi_j\,\Delta HMain_{i,t-j} \\ &\quad + \sum_{j=0}^{J} \psi_j\,\Delta HInv_{i,t-j} + \Gamma' Z_{i,t} + \varepsilon_{i,t},\end{aligned} \tag{29}$$

where $Z_{i,t}$ includes contemporaneous shocks and macro controls. The lag coefficients indicate that maintenance reductions have effects that cumulate over multiple years, with a pattern consistent with deferred servicing and gradual equipment downtime accumulation. Investment reductions also matter, but their effect on short-run functionality is weaker than maintenance, consistent with the idea that the existing stock can function if maintained, while new investment takes time to translate into operational capacity. This distinction is important for interpreting fiscal space: maintaining a minimum maintenance floor may have a relatively high resilience payoff in constrained states, even if expanding the stock is not feasible [45].

Heterogeneity analyses suggest that institutional capacity moderates the transmission of sovereign stress to health infrastructure outcomes. Countries with stronger cash management and procurement systems exhibit smaller declines in functionality for a given financing shock, even when investment declines are similar. This is consistent with the role of execution efficiency and the ability to reallocate within budgets to protect critical maintenance and supply chains. Conversely, in lower-capacity settings, financing shocks are associated with both large investment compression and sharp increases in payment delays, which then translate into rapid functionality deterioration. These patterns remain when controlling for income levels, urbanization, and baseline health spending shares, indicating that institutional differences are not fully captured by development proxies.

Debt composition and refinancing risk appear to play a central role in resilience outcomes. When external debt shares are high and maturities are short, financing shocks translate into larger exchange-rate adjustments and sharper liquidity constraints, which are associated with steeper declines in health capital execution and payment reliability. In contrast, when debt is predominantly long-maturity and concessional, the same global risk shocks have weaker pass-through to domestic fiscal compression, and health maintenance tends to be less volatile [46]. This result is consistent with the model channel in which rollover risk and convex risk premia create a high-stress regime where small shocks trigger disproportionate adjustment. It is also consistent with the view that resilience is partly a function of fiscal volatility rather than only the average spending level.

The empirical results also evaluate the role of external financing earmarked to health infrastructure. In settings where external funds are structured to cover capital costs without supporting operations and maintenance, investment execution can rise without corresponding improvements in functionality. This pattern is visible when capital execution is instrumented by large disbursement episodes that are plausibly orthogonal to contemporaneous domestic shocks, while maintenance and payment reliability remain constrained. The resulting mismatch is associated with smaller improvements in service retention than would be predicted by capital execution alone. When external financing is accompanied by mechanisms that stabilize maintenance and procurement, the association between investment and functionality is stronger, consistent with lifecycle financing and complementarity.

Robustness analyses address alternative measurements and potential confounding [47]. Using alternative dependent variables such as health capital budget shares, public investment execution rates, or equipment procurement volumes yields qualitatively similar results regarding the negative association of financing stress with infrastructure-related outlays. Using alternative financing stress indicators, including changes in domestic yields, reserve drawdowns, or episodes of payment arrears on external obligations, preserves the main patterns. Controlling for conflict incidence and governance shocks does not remove the spread and debt service associations, though magnitudes can change, which is expected because conflict can drive both fiscal stress and direct infrastructure damage. In specifications that explicitly include disaster damage proxies, the financing variables retain explanatory power for functionality, indicating that the results are not solely driven by physical destruction.

To translate empirical estimates into resilience-relevant scenarios, the study combines the dynamic responses from the local projections with the estimated mapping from spending and payment reliability into functionality and service retention. This yields a counterfactual decomposition of how much of the service disruption following a financing shock is associated with investment compression, maintenance compression, and payment delays. The decomposition suggests that in many cases, payment reliability and maintenance account for a sizable share of the medium-run disruption, while investment compression accounts for a large share of the longer-run vulnerability by slowing the replenishment and upgrading of the capital stock. This interpretation aligns with the state-space estimates in which latent functionality responds strongly to maintenance and payment reliability and less immediately to investment flows [48].

The empirical results should be interpreted with care because measurement error is substantial, and the set of facility readiness indicators is not uniformly available. The state-space approach partially addresses this limitation by pooling information across indicators and allowing for noisy signals, but identification remains stronger for changes around major financing stress episodes than for slow-moving trends. In addition, health sector classification differences across countries can introduce non-classical measurement error in maintenance proxies, and project financing off-budget can obscure true investment levels. These issues motivate an emphasis on patterns that are consistent across multiple measurement choices and on dynamic responses that align with institutional narratives of how fiscal stress transmits to execution reliability.

Taken together, the empirical results support the central mechanism that sovereign debt dynamics and financing conditions affect healthcare infrastructure resilience primarily through spending composition and execution reliability rather than through a stable linear relationship between debt levels and health outcomes. Financing shocks and high debt service burdens are associated with reductions in health capital execution, sustained maintenance compression, and deteriorations in payment reliability, which in turn are associated with lower facility functionality and weaker service retention during stress. The nonlinear amplification in high-debt and high-refinancing-need states is consistent with convex risk premia and binding liquidity constraints, reinforcing the policy relevance of debt composition, maturity management, and institutional mechanisms that protect maintenance and supplier payment discipline under stress. These empirical findings complement the integrated stochastic framework by providing evidence that the principal transmission channels operate through volatility and execution, implying that resilience-oriented fiscal design requires not only additional resources but also financing structures and institutions that reduce the probability and severity of disruptive fiscal adjustment [49].

VII. Conclusion

Fiscal space and sovereign debt dynamics shape healthcare infrastructure resilience through intertemporal constraints, liquidity pressures, and the composition and execution of spending. In low- and middle-income economies, these channels are amplified by volatile financing conditions, exposure to external shocks, and institutional frictions that translate macro stress into payment delays, procurement disruptions, and deferred maintenance. Resilience is therefore not solely an engineering attribute of buildings and equipment; it is a macro-fiscal and institutional outcome that depends on whether the sovereign can sustain the recurrent and lifecycle costs that make infrastructure functional.

The integrated stochastic framework developed in this paper clarifies several mechanisms that are often discussed separately. Debt dynamics affect borrowing costs and market access, which influence the feasibility of countercyclical spending and the likelihood of disruptive adjustment. Spending volatility and arrears directly reduce infrastructure functionality even without physical damage, and undermaintenance accelerates depreciation in ways that can be nonlinear. Shocks can simultaneously increase health service demand, damage assets, and tighten financing conditions, making resilience investments most valuable precisely when they are hardest to fund. The model also highlights why debt composition, maturity structure, and contingent liabilities matter for health outcomes: they govern the probability of liquidity crises that compress budgets and degrade functionality [50].

Policy implications follow from the structure of these channels rather than from a single numerical threshold. When financing is stable and debt is moderate, resilience-oriented investment and maintenance protection can be pursued alongside expansion, with attention to lifecycle financing and execution quality. When debt is high and risk premia are convex, strategies that stabilize functionality through protected maintenance, reliable supplier payments, and efficiency improvements can yield higher resilience per unit of fiscal space than large expansion projects. Debt management that reduces rollover risk, financing modalities that align with long-run maintenance needs, and fiscal frameworks that protect essential lifecycle expenditures can reduce the probability of resilience failures. External financing and debt treatments can have resilience value by lowering not only average financing costs but also the volatility of spending execution and the likelihood of entering high-stress financing regimes.

Operationalizing these insights requires measurement systems that connect macro variables to facility functionality and service capacity. Although data constraints are real, combining budget execution data, debt statistics, facility readiness indicators, and procurement and payment information can support state-space estimation and scenario-based stress testing. Such analyses can inform medium-term planning by testing whether proposed investment paths are compatible with plausible fiscal and debt trajectories, and by identifying which instruments most effectively preserve service continuity under adverse states. In this way, fiscal space can be treated not as a static number but as a probabilistic, institution-dependent capacity to sustain resilient healthcare infrastructure over time [51].

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