

Beyond Health Infrastructure: Capacity, Supply Chain Dependencies, and Early Warning Signals of Health System Collapse

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Abstract

Health system infrastructure is commonly assessed through healthcare facilities, equipment, and physical resources; however, the continuity of essential services also depends on operational capacity, supply chains, and critical systems beyond the health sector. This study aimed to identify infrastructure-, capacity-, and supply-related vulnerabilities and develop an early warning framework for detecting deterioration before health system functional failure or collapse.

This is a qualitative exploratory study was conducted using semi-structured interviews with 15 experts in health policy and management, health systems research, infrastructure, logistics, and supply chain management. Thematic analysis was used to identify dimensions, dependencies, failure pathways, and measurable warning signals. Findings were subsequently mapped to the Stability–Efficiency–Adaptability (SEA) model.

Analysis generated a five-level framework extending from national critical infrastructure and strategic systems to health-system networks, regional and distribution systems, healthcare facilities, and point-of-care availability. Infrastructure, capacity, and supply chains emerged as distinct but functionally interdependent domains. Capacity deterioration followed a progression from nominal to available, functional, accessible, and effective capacity. Supply chain vulnerability extended from raw materials and active pharmaceutical ingredients through manufacturing, procurement, importation, transportation, storage, distribution, and point-of-care availability, encompassing both medical and critical non-medical inputs. Expert-derived indicators were classified across five risk levels from Safe to Near Collapse. SEA analysis highlighted the importance of stability, resource-use efficiency, and adaptive buffers, including redundancy, reserves, alternative suppliers, routes, and surge capacity.

Early warning assessment should move beyond physical healthcare infrastructure toward monitoring functional capacity, upstream dependencies, supply continuity, redundancy, and adaptive reserve. Detecting deterioration across these interconnected domains may provide an earlier opportunity for intervention before system saturation progresses to functional failure and collapse.

Keywords: Health system collapse; Health infrastructure; Healthcare capacity; Supply chain; Critical infrastructure; Early warning signals; Health system resilience; SEA model

1. Introduction

Health systems depend on the coordinated functioning of infrastructure, service capacity, and supporting resources to maintain essential care under both routine conditions and periods of

disruption. Contemporary resilience frameworks therefore emphasize integrated monitoring of health-system capacities, resources, medical products, infrastructure, and service continuity across national, subnational, and service-delivery levels (World Health Organization [WHO], 2024a, 2024b).

Healthcare infrastructure, however, extends beyond hospitals, clinics, and medical equipment. Essential services depend on electricity, water, sanitation, transportation, communication, logistics, and other critical systems that may lie partly outside the formal health sector. Reliable electricity, for example, is required for medical equipment, refrigeration, information and communication technologies, water, sanitation, lighting, ventilation, and other essential facility functions (WHO, 2023). The same evidence demonstrates that unreliable electricity can reduce equipment availability, disrupt sterilization and water services, and compromise inpatient, outpatient, vaccination, delivery, and laboratory services (WHO, 2023; Sängner et al, 2021; Guidotti et al. 2016).

The distinction between the physical presence of infrastructure and its actual functionality is therefore important. A health facility may technically have electricity or backup generation while the supply remains unreliable, generation capacity is only partly functional, or fuel availability prevents continuous operation (WHO, 2023). Similarly, hospital resilience depends not merely on installed resources but on the ability to mobilize staff, supplies, fuel, electricity, space, and alternative resources when demand increases or routine systems are disrupted (Khalil et al., 2023). These findings suggest that nominal capacity may differ substantially from the capacity that remains functional and usable under stress.

Health-system functionality is also influenced by dependencies between wider infrastructure networks. Interdependent systems may operate efficiently under normal conditions, yet disruption in one network can propagate to others and produce cascading failures and broader loss of functionality (Guidotti et al., 2016). Such dependencies may be physical, cyber, geographic, or logical, and can increase both the magnitude of service loss and the time required for recovery (Guidotti et al., 2016).

Supply chains create an additional layer of vulnerability. Pharmaceutical products may depend on raw materials, active pharmaceutical ingredients (APIs), manufacturing, and other components distributed across several countries before reaching the patient (Suda & Tadrous, 2021). Disruptions related to manufacturing, sole-source arrangements, trade, geopolitical instability, weather events, pandemics, or sudden demand changes can therefore affect downstream availability (Suda & Tadrous, 2021). Supply continuity also depends on coordination among API suppliers, manufacturers, distributors, stockpile authorities, and health-system end users, as well as on transparency, traceability, and strategic reserves (Patel et al., 2023).

Taken together, these findings indicate that infrastructure, capacity, and supply chains are analytically distinct but operationally interconnected. Infrastructure failures can reduce usable capacity and disrupt supply flows, while supply-chain failures can render otherwise intact infrastructure and nominal capacity functionally ineffective. WHO has therefore called for more holistic monitoring of healthcare-facility infrastructure and coordinated assessment of critical services rather than fragmented measurement of individual components (WHO, 2023).

Previous research using the Stability–Efficiency–Adaptability (SEA) framework conceptualizes health-system collapse as a progressive saturation-driven process rather than solely as a sudden catastrophic event. Infrastructure and supply-chain vulnerability were identified as important determinants of collapse, particularly where systems optimized for normal conditions lack redundancy and shock-absorption capacity (Manafi, 2025, 2026; Hojabri & Manafi, 2026a). The SEA framework interprets sustainability through the interaction of Stability, Efficiency, and

Adaptability, and provides a basis for identifying accumulating pressures before they progress toward systemic saturation and failure (Hojabri & Manafi, 2026 a,b,c,d,e ; Gutowski et al ,2026).

The problem addressed by this study is that a health system may appear adequately resourced when assessed through physical infrastructure, nominal capacity, or current supply availability while its effective ability to deliver care is already being weakened by external infrastructure dependencies, upstream supply-chain vulnerabilities, inadequate redundancy, or declining operational capacity. Although existing literature addresses critical infrastructure, hospital capacity, supply-chain resilience, and health-system resilience, these areas are commonly examined separately and are not sufficiently integrated within a multilevel early-warning framework focused on progression toward health-system saturation and collapse. The present study therefore aims to integrate infrastructure, capacity, and end-to-end supply-chain dependencies across national critical systems, health-system networks, regional and distribution systems, healthcare facilities, and the point of care; identify measurable early-warning indicators and progressive risk levels; and interpret these signals through the SEA model to support earlier recognition of deterioration before widespread functional failure occurs.

2. Literature Review

The literature increasingly conceptualizes health infrastructure as more than the physical stock of hospitals, buildings, beds, and medical equipment. Contemporary health-system resilience approaches incorporate infrastructure within a broader network of medical products, technologies, logistics, utilities, service-delivery resources, and intersectoral dependencies. WHO guidance recommends assessing gaps in medical products, supplies, technologies, and infrastructure together and establishing mechanisms for interoperability, mutual aid, surge capacity, and coordination across health and allied sectors (World Health Organization [WHO], 2024a). This perspective is important because the functionality of healthcare assets depends on systems that frequently extend beyond the organizational boundaries of the health sector.

Electricity provides one of the clearest examples of this dependency. Reliable electricity is required for medical equipment and information and communication technologies but also supports refrigeration, lighting, clean water, sanitation, ventilation, and cooling. Consequently, energy reliability influences multiple clinical and operational functions simultaneously (WHO, 2023). Evidence reviewed by WHO further associates inadequate or unreliable electricity with reduced availability of essential equipment, problems with water supply and sterilization, and reduced readiness of inpatient, outpatient, vaccination, delivery, and laboratory services (WHO, 2023).

Water infrastructure represents a comparable dependency. Sanger et al. (2021), in a systematic review of water-supply failures in healthcare facilities, argue that critical health-infrastructure resilience remains overly dominated by a technical perspective. Their findings show that healthcare disruptions are shaped by interactions among technical failures, natural hazards, and social and organizational preparedness and that technical measures alone are insufficient to ensure healthcare-facility resilience. Their analysis of cascading consequences of water disruption is particularly relevant because it shifts infrastructure assessment from the question of whether an asset exists toward whether the interconnected services necessary for healthcare remain functional.

This distinction is reflected in WHO's resilience indicators. Infrastructure standards include structural safety but also adequate and accessible space, capacity for surge, WASH, healthcare-waste systems, sustainable energy, and appropriate information technologies. Importantly, WHO links these standards to the **safety and functionality** of facilities and their ability to maintain essential services during routine conditions and unexpected shocks (WHO, 2024b). Infrastructure

resilience therefore involves both the physical integrity of healthcare assets and the continued functioning of the systems required to operate them.

Infrastructure Interdependency and Cascading Failure

Critical-infrastructure research provides an important theoretical basis for understanding why apparently localized failures can produce health-system consequences. Guidotti et al. (2016) demonstrate that infrastructure networks are interconnected through exchanges of resources and information. Under normal conditions, these interdependencies can improve efficiency and allow systems to operate closer to design capacity; under disrupted conditions, however, failure can propagate between networks and result in wider and more abrupt system dysfunction than would occur in isolated systems.

This introduces a central distinction between direct failure and cascading failure. A healthcare facility may not itself experience structural damage yet lose functionality because electricity, water, transportation, communication, or another supporting network has failed. Guidotti et al. (2016) further show that interdependencies affect not only the magnitude of functional loss but also recovery trajectories, making dependency relationships relevant to both vulnerability assessment and restoration planning.

Healthcare-specific literature reaches a similar conclusion. Sanger et al. (2021) demonstrate that water disruption cannot be adequately interpreted as an isolated technical problem because its consequences depend on organizational arrangements and interconnected services. Their review explicitly calls for broader socio-technical approaches and organizational strategies capable of managing cascading impacts. The literature therefore supports an interpretation of healthcare infrastructure as a **system of dependencies**, rather than simply an inventory of physical assets.

The implications extend beyond utilities. Sanger et al. also note that disruption of public transport can affect staff mobility and therefore healthcare operability, illustrating how infrastructure outside the health sector can indirectly alter healthcare capacity. This supports a distinction between health infrastructure and critical non-health infrastructure on which healthcare depends, while recognizing that the two become operationally inseparable when continuity of care is considered.

Capacity as a Functional Rather Than Nominal Resource

The literature on hospital resilience similarly challenges purely quantitative interpretations of capacity. Khalil et al. (2023) found that maintaining hospital functionality during shocks requires rapid mobilization of human, material, and financial resources. Across resource-constrained and emergency settings, shortages of health workers, emergency and ICU specialists, supplies and fuel, together with electricity outages, impaired hospitals' ability to respond to increased demand.

Capacity therefore cannot be represented adequately by the number of installed beds, rooms, equipment, or facilities alone. Hospital performance depends on interactions among physical space, staff, supplies, operational systems, and the ability to mobilize these resources. Khalil et al. (2023) describe the interaction between hospital physical space and its users as central to performance and functionality and emphasize the combined importance of structural and functional resilience.

Surge capacity further illustrates this distinction. During earthquakes and other emergencies, hospitals have increased staffing, redistributed or transferred patients, and mobilized alternative resources to maintain functionality. The hospital-resilience literature identifies redundancy the ability to duplicate or mobilize alternatives as particularly important when disruption becomes prolonged (Khalil et al., 2023). Resourcefulness and substitution of services, facilities, and resources have similarly been identified as mechanisms through which hospitals preserve functionality under pressure.

These findings provide conceptual support for distinguishing between the resources nominally possessed by a system and those that remain operationally usable. While the reviewed literature does not consistently employ the exact sequence of nominal, available, functional, accessible, effective capacity developed in the present study, it repeatedly differentiates physical resources from functionality, mobilization, accessibility, redundancy, and the ability to deliver services. The proposed capacity sequence in this study therefore represents an integration and further operationalization of concepts that appear across the resilience literature rather than terminology directly adopted from a single previous framework.

Supply Chains as End-to-End Dependency Networks

Supply-chain literature extends this dependency perspective beyond infrastructure. Healthcare supply chains are complex networks involving upstream production, intermediate inputs, manufacturers, distributors, procurement systems, logistics, inventories, and healthcare organizations. Suda and Tadrous (2021) provide a particularly clear illustration: a medicine used in one country may be manufactured in another, while its API is produced in a third country and additional non-medical and chemical components originate elsewhere.

This means that the availability of a finished product may depend on events occurring at geographically distant and operationally upstream stages. Suda and Tadrous (2021) identify geopolitical events, trade disruption, civil unrest, weather, pandemics, manufacturing problems, sole-source contracts, and demand increases among the factors capable of contributing to shortages. Their analysis therefore demonstrates why monitoring only the final product or facility stock level can obscure vulnerabilities developing earlier in the chain.

OECD (2024) provides further evidence regarding geographical and production concentration. Medical supply chains have become increasingly internationalized, while manufacturing of both finished pharmaceutical products and APIs remains geographically concentrated in parts of the market. In some supply chains, dependence on a small number of geographically concentrated API producers creates vulnerability because localized disruptions can affect wider product availability. Importantly, OECD also notes that reshoring selected production activities does not necessarily eliminate external dependency because firms may relocate some core activities while continuing to rely on offshore production or inputs for others.

These findings challenge the assumption that domestic final production is equivalent to supply-chain independence. Supply security must instead be assessed across the stages required to produce and deliver the final product. OECD's analysis explicitly considers FPPs, APIs, procurement, shortages, diversification, and crisis capabilities as interconnected dimensions of medical supply-chain security. This multistage structure closely supports the need to examine raw materials and APIs alongside manufacturing, procurement, transportation, storage, and final distribution.

Concentration, Redundancy, and Supply-Chain Adaptability

The literature identifies concentration and lack of alternatives as major sources of supply vulnerability. OECD (2024) highlights excessive manufacturing concentration as one source of shortages and identifies diversification and increased flexibility and agility as potential strategies for reducing exposure to disruption. Concentration can also be quantified. The OECD report discusses the Herfindahl–Hirschman Index as a measure based on supplier market shares, providing a potential quantitative approach for assessing supplier concentration.

The healthcare supply-chain resilience literature broadens this further. Zamiela et al. (2022) identify a set of resilience enablers including agility, security, supply-network design, communication capability, risk management, collaboration, flexibility, robustness, sustainability, velocity, redundancy, and awareness. Of particular relevance to early warning, they define redundancy in terms of extra stock that can be mobilized during emergencies and

awareness/sensitivity as the ability to anticipate demand and recognize possible disruption through early-warning mechanisms.

Patel et al. (2023) similarly emphasize the importance of visibility across the chain. They describe supply-chain coordination extending from API suppliers through manufacturers and distributors to health-system end users and argue that information sharing improves transparency, traceability, and the ability of each actor to prepare for emerging supply problems. They also identify strategic stockpiling as a risk-management mechanism requiring coordination among manufacturers, stockpile authorities, and hospitals, as well as information about discontinuations and interruptions affecting materials or products.

The consequences of insufficient redundancy are illustrated by real supply disruptions. Patel et al. describe how Hurricane Maria damaged a manufacturing plant that supplied approximately half of the small-volume saline bags used by U.S. hospitals; because other manufacturers could not sufficiently increase production, disruption at one production site contributed to a major shortage. The example demonstrates how concentration plus limited substitution capacity with disruption can convert an upstream production failure into downstream healthcare consequences.

From Supply Disruption to Point-of-Care Consequences

A significant theme across the literature is that shortages visible to healthcare providers represent downstream manifestations of vulnerabilities that may have developed much earlier. Patel et al. (2023) describe product delays and drug shortages as consequences of interacting problems involving increased demand, sourcing difficulties, traceability limitations, and labor shortages. They argue that anticipating supply problems allows downstream organizations to prepare before shortages fully materialize.

WHO's resilience indicators primarily capture several important downstream or preparedness conditions, including prepositioned essential supplies, availability of essential medicines, interruptions in water supply, power outages, and facility infrastructure standards (WHO, 2024b). The indicator framework also includes standard operating procedures for ensuring the availability of medicines, PPE, oxygen, and other essential supplies during shocks or surges.

These measures are important for resilience monitoring, but supply-chain literature suggests that additional warning signals can exist further upstream. Supplier concentration, geographic concentration, dependence on limited API sources, declining redundancy, production interruption, information gaps, and limited alternative sourcing may emerge before facility-level stock-outs. OECD (2024), for example, explicitly distinguishes policies aimed at anticipating risks of shortages, reducing exposure to those risks, and developing additional capabilities for severe crises. This distinction supports a shift from shortage monitoring alone toward monitoring the conditions that make future shortages increasingly probable.

Early Warning, Reserves, and Adaptive Buffers

The reviewed literature consistently identifies redundancy and reserve capacity as important components of resilience. At hospital level, Khalil et al. (2023) associate resilience during prolonged responses with the ability to duplicate or mobilize alternative resources. At supply-chain level, Zamiela et al. (2022) identify redundancy, flexibility, agility, and awareness of possible disturbances as central resilience enablers. Patel et al. (2023) identify strategic stockpiles as one mechanism for reducing the consequences of shortages.

WHO adopts a similar operational perspective. Its resilience guidance calls for identification of gaps in supplies, technologies, and infrastructure; mechanisms for mutual aid; and arrangements supporting surge capacity in supplies, logistics, and infrastructure (WHO, 2024a). The resilience indicator package further recommends monitoring at national, subnational, and facility levels and

includes early-warning systems, multisectoral information sharing, vulnerability mapping, prepositioned supplies, medicine availability, water interruption, and power outages (WHO, 2024b).

The literature therefore suggests that the condition of a system cannot be inferred from disruption alone. Two systems exposed to a similar disruption may experience very different consequences depending on redundancy, reserve stocks, alternative suppliers, alternative infrastructure, surge capability, and capacity for substitution. This provides an important basis for interpreting adaptive buffers as part of early warning: deterioration becomes more consequential when the resources available to compensate for disruption are themselves being depleted.

From Resilience Monitoring to Collapse-Oriented Early Warning

Although resilience measurement has advanced substantially, it is conceptually different from monitoring progression toward collapse. WHO's resilience indicator package is explicitly intended to support routine and shock-related monitoring from national to subnational and facility levels, with indicators integrated into routine information systems and defined against baselines and targets (WHO, 2024b). This provides an important measurement foundation but is principally oriented toward the capacities required to build and maintain resilience.

Previous work within the SEA research programme addresses a different but complementary question: whether accumulating pressures can be detected before they progress to saturation and functional failure. The initial collapse study describes healthcare-system collapse as a progressive, saturation-driven process and identifies infrastructure and supply-chain vulnerability among the principal determinants interacting across Stability, Efficiency, and Adaptability (Hojabri & Manafi, 2026 a,b,c,d,e). In that framework, infrastructure and supply chains become particularly vulnerable where systems are optimized for normal conditions without sufficient redundancy or shock absorption.

The same study identifies a limitation in conventional KPI and resilience approaches: indicators may describe performance or resilience but remain fragmented and may not provide a theoretically integrated signal of progression toward saturation and impending system failure (Gutowski et al 2026; Hojabri & Manafi, 2026 a,b). The distinction is important. A resilience framework asks whether capacities exist to withstand and adapt to shocks; a collapse-oriented early-warning framework additionally asks whether those capacities are deteriorating, how quickly adaptive buffers are being consumed, and how close the system may be to losing essential functionality.

Viewed through SEA, the literature reviewed here can be interpreted across three related dimensions. Stability concerns continuity of infrastructure, supplies, utilities, and essential service functionality. Efficiency concerns the conversion and allocation of available infrastructure, supplies, logistics, and capacity into usable services. Adaptability is reflected in redundancy, surge capacity, alternative suppliers, substitution, flexibility, stockpiles, resource mobilization, and the ability to reorganize services when normal arrangements fail. The hospital and supply-chain literature provide substantial empirical support for these adaptive mechanisms, particularly redundancy, flexibility, resourcefulness, alternative resources, and early recognition of disruption (Khalil et al., 2023; Zamiela et al., 2022).

Taken together, the literature establishes several important components of infrastructure and supply-chain resilience. First, healthcare infrastructure is dependent on external systems such as electricity, water, transportation, and communications and therefore cannot be evaluated exclusively through physical health-sector assets (WHO et al., 2023; Sanger et al., 2021). Second, capacity is determined not only by installed resources but by functionality, resource mobilization, redundancy, and the ability to accommodate surge (Khalil et al., 2023). Third, medical supply chains extend from upstream inputs such as APIs through production and distribution to healthcare

end users and may contain substantial geographic, manufacturing, and supplier concentration (Suda & Tadrous, 2021; OECD, 2024). Finally, interdependencies allow disruption in one component to propagate across other infrastructure and service networks, creating cascading functional consequences (Guidotti et al., 2016).

However, these bodies of literature remain largely organized around critical-infrastructure resilience, hospital resilience, surge capacity, supply-chain resilience, or health-system resilience measurement. They provide substantial evidence about individual vulnerabilities and adaptive mechanisms, but do not fully integrate them into a single multilevel framework describing how infrastructure, capacity, and end-to-end supply dependencies interact as a health system moves from structural vulnerability through deterioration toward saturation and potential collapse. Existing resilience indicators also capture important conditions such as infrastructure standards, power and water interruption, essential supplies, and medicine availability, but the reviewed literature provides less integrated operationalization of upstream dependency, loss of redundancy, depletion of adaptive buffers, and the widening difference between resources nominally present and those that remain effectively usable.

The present study addresses this gap by integrating Infrastructure, Capacity, and Supply Chain within a five-level structure extending from national critical systems to the point of care. Rather than treating infrastructure failure, capacity saturation, and supply shortages as separate outcomes, the framework examines the dependencies through which deterioration can propagate across these domains. It further extends existing resilience concepts by distinguishing nominal, available, functional, accessible, and effective capacity; following supply dependencies from upstream inputs to point-of-care availability; and translating structural dependency, redundancy, reserve depletion, and functional deterioration into measurable early-warning indicators. Within the SEA framework, this enables the analysis to move from describing whether a health system is resilient toward identifying when Stability is deteriorating, how Efficiency is being affected, whether Adaptability remains sufficient to compensate, and when depletion of adaptive capacity may signal progression toward saturation and functional collapse.

3. Methodology

This study employed a qualitative exploratory design based on semi-structured expert interviews to identify the dimensions, vulnerabilities, dependencies, and early warning signals associated with infrastructure, capacity, and supply chain conditions that may contribute to health system saturation and collapse. A qualitative approach was selected because the resources required to maintain healthcare delivery extend beyond conventional health infrastructure and may involve complex interactions between health-sector assets, operational capacities, supply systems, and critical supporting systems outside the health sector.

Participants were selected through purposive sampling based on their professional experience and ability to provide a system-level perspective on healthcare infrastructure, service capacity, logistics, supply chains, health system management, and continuity of essential services. A total of 15 experts representing three complementary areas of expertise participated in the study (Table 1).

Table 1. Distribution and Characteristics of Expert Participants

Expert Group	Number (n)	Main Areas of Expertise
Health policymakers and senior health managers	4	Health policy, planning, regulation, system management, and emergency preparedness

Academics and health system researchers	6	Health systems, public health, resilience, healthcare management, and health services research
Infrastructure, capacity, logistics, and supply chain experts	5	Healthcare infrastructure, operational capacity, procurement, logistics, supply chain, and continuity planning
Total	15	

Data had collected through semi-structured interviews lasting approximately 45–60 minutes. Interviews had conducted either face-to-face or through online platforms according to participant preference and availability. The interview questions were designed to allow participants to identify relevant dimensions and subdimensions without imposing a predetermined classification of infrastructure, capacity, or supply chain vulnerability. Participants were encouraged to consider not only resources located within the health sector but also external systems and resources upon which continuous healthcare delivery depends.

The interviews explored the resources required to maintain essential services, conditions capable of reducing their functionality or availability, dependencies between health and non-health systems, and mechanisms through which localized disruption could propagate across the system. Supply chain vulnerability was examined beyond the final occurrence of shortages by exploring where disruption may emerge along the chain through which essential medical and non-medical resources reach healthcare services. The interviews also sought observable or measurable changes that could indicate deterioration before substantial capacity loss, service interruption, or system failure became evident. See Table 2.

Table 2. Semi-Structured Interview Questions and Analytical Purpose

No.	Interview Question	Analytical Purpose
Q1	What infrastructure, capacities, resources, and supporting systems are essential for maintaining the continuous delivery of essential health services?	Identify the major dimensions and subdimensions required for health system functioning, including resources and dependencies within and beyond the health sector.
Q2	What weaknesses, shortages, disruptions, or dependencies in these areas could progressively reduce the ability of a health system to maintain essential services or move it toward saturation or failure?	Identify vulnerabilities, bottlenecks, critical dependencies, and pathways through which fragility may progress toward functional deterioration.
Q3	How can disruptions originating outside the health sector affect healthcare infrastructure, available capacity, access to services, and continuity of care?	Explore health system dependence on external supporting systems and identify interdependencies and potential cascading effects.
Q4	Where can disruptions arise along the chain through which essential medical and non-medical resources reach healthcare services, and how can problems at one stage affect	Identify supply chain stages, bottlenecks, medical and non-medical dependencies, and upstream-to-downstream disruption pathways.

	subsequent stages and point-of-care availability?	
Q5	What observable or measurable changes could provide early warning that these systems are deteriorating before major shortages, service interruption, capacity loss, or health system failure becomes evident?	Identify potential early warning signals and distinguish earlier indicators of vulnerability from downstream manifestations of failure.

Interview data were analyzed using thematic analysis. Initial coding was conducted inductively to identify recurring concepts related to infrastructure, capacity, supply chains, critical dependencies, vulnerabilities, and mechanisms contributing to deterioration in health system functioning. Related codes were subsequently organized into higher-order dimensions and subdimensions. This inductive approach allowed the conceptual structure to emerge from expert evidence rather than imposing predetermined categories on the interview data.

Particular attention was given to interdependencies between health-sector resources and external supporting systems and to mechanisms through which disruption in one component could generate secondary or cascading effects elsewhere in the system. The analysis also examined differences between the nominal existence of resources and their actual availability, functionality, and accessibility. For supply chains, disruption was examined across the stages identified through the interviews, including upstream, logistical, distributional, and point-of-care processes where supported by the data.

Following the inductive analysis, the identified dimensions, subdimensions, and early warning signals were mapped to the Stability–Efficiency–Adaptability (SEA) model. Stability represented the ability to maintain reliable and continuous essential functions; Efficiency reflected the effective use, allocation, and distribution of available infrastructure, capacity, and supplies; and Adaptability represented the ability to absorb disruption, mobilize alternatives, expand or reconfigure capacity, and maintain essential services under changing conditions.

As a complementary structural analysis, the findings were also mapped against the WHO Six Building Blocks service delivery, health workforce, health information systems, access to essential medicines, health financing, and leadership/governance to identify where infrastructure-, capacity-, and supply-related vulnerabilities intersect with established health system functions.

Finally, potential early warning signals were linked to the empirically derived dimensions and SEA domains. Particular attention was given to distinguishing upstream indicators of emerging vulnerability from downstream manifestations of failure, such as severe shortages, loss of functional capacity, service interruption, or inability to maintain essential healthcare delivery. The resulting dimensions, interdependencies, failure pathways, and indicators formed the basis for subsequent development of the study's early warning framework.

4. Results

Thematic analysis of the expert interviews identified infrastructure, capacity, and supply chain as distinct but functionally inseparable components of health system continuity. Infrastructure represented the physical and technical foundation required for healthcare delivery; capacity represented the extent to which available resources could actually support healthcare demand; and supply chains represented the continuous flow of medical and non-medical inputs required to maintain infrastructure and service capacity in operation.

Although the three components could be examined independently, participants repeatedly described dependencies across them. Infrastructure without the utilities, maintenance, supplies, and operational resources required for its use did not necessarily translate into functional capacity. Similarly, nominal capacity could decline substantially in practice when infrastructure became unavailable, supply chains were disrupted, or access to services was constrained. Supply chain disruption could therefore reduce capacity even when physical infrastructure remained intact.

The analysis further demonstrated that relevant infrastructure and supply dependencies extended beyond the formal boundaries of the health sector. Electricity and energy systems, water, transportation networks, roads, ports, telecommunications, fuel, logistics, and other critical supporting systems were identified as essential for maintaining healthcare operations.

Supply dependency also extended substantially upstream of healthcare facilities. Experts identified vulnerabilities involving raw materials, active pharmaceutical ingredients (APIs), critical components, manufacturing inputs, production capacity, suppliers, geographic sources, import routes, transportation corridors, storage, and distribution. Domestic production of a finished product was therefore not considered equivalent to supply independence when critical upstream inputs remained externally dependent.

These findings supported integration of infrastructure, capacity, and supply chain into a single analytical framework while retaining the distinct contribution of each domain.

Five-Level Infrastructure, Capacity, and Supply Chain Framework

The analysis identified five interconnected system levels extending from national critical systems to actual service availability at the point of care. The structure represented a progressive transition from predominantly external and national dependencies toward direct healthcare functionality. Table 3 shows Five-Level Infrastructure, Capacity, and Supply Chain Framework.

Table 3. Five-Level Infrastructure, Capacity, and Supply Chain Framework

Level	Infrastructure	Capacity	Supply Chain	Orientation
Level 1. National Critical Infrastructure and Strategic Systems	National electricity and energy systems; water systems; roads; transportation networks; ports; airports; telecommunications; critical industrial infrastructure	National energy, water, transport, logistics, production, import and strategic reserve capacity	Raw materials; APIs/components; manufacturing inputs; international sourcing; domestic production; import routes; strategic reserves	Predominantly national/non-health
Level 2. Health-System Infrastructure and National Supply Networks	National healthcare network; hospitals; laboratories; blood systems; central warehouses; referral and emergency infrastructure	National bed, ICU, diagnostic, laboratory, emergency, referral and	National procurement; central purchasing; medical supply networks; central inventories;	Predominantly health; dependent on Level 1

		surge capacity	national distribution	
Level 3. Regional and Local Service and Distribution Systems	Regional healthcare facilities; warehouses; roads; transportation and communication links	Regional service, emergency, ambulance, referral, storage, logistics and reserve capacity	Regional allocation; storage; transportation; replenishment and distribution	Health–non-health interface
Level 4. Healthcare Facility Operational Level	Facility buildings; electricity; water; generators; oxygen systems; medical equipment; IT; waste systems	Operational beds; ICU; operating rooms; diagnostics; emergency services; facility surge capacity	Facility inventories; medicines; oxygen; blood products; devices; consumables; fuel; food; spare parts; maintenance inputs	Healthcare operational
Level 5. Point-of-Care and Patient-Accessible Level	Functional clinical spaces and immediately usable equipment	Capacity actually available, functional and accessible to patients	Required medicines, devices, consumables and supporting inputs available at the required time and location	Patient/service level

Participants described these levels as vertically interconnected rather than independent. Disruption at higher levels could propagate downward through the system, while severe local failures could redistribute demand toward other facilities and contribute to regional or system-wide saturation.

Health and Non-Health Infrastructure Dependencies

Two broad infrastructure categories emerged from the interviews: direct health infrastructure and critical supporting infrastructure. Direct health infrastructure included hospitals, primary healthcare facilities, laboratories, warehouses, medical equipment, oxygen systems, emergency and referral infrastructure, and other assets directly involved in healthcare delivery. Critical supporting infrastructure included electricity and energy, water, transportation, roads, ports and airports, telecommunications, fuel systems, logistics infrastructure, and other services that may be managed outside the health sector but are required for healthcare operations.

Participants emphasized that the physical existence of infrastructure did not guarantee its operational contribution to healthcare. Infrastructure functionality depended on continuous

utilities, maintenance, spare parts, technical support, fuel, access routes, communications, and other enabling conditions.

From Nominal Capacity to Effective Capacity

A consistent distinction emerged between nominal health system capacity and the capacity actually usable for healthcare delivery. Five sequential states were identified that shown in table no 4.

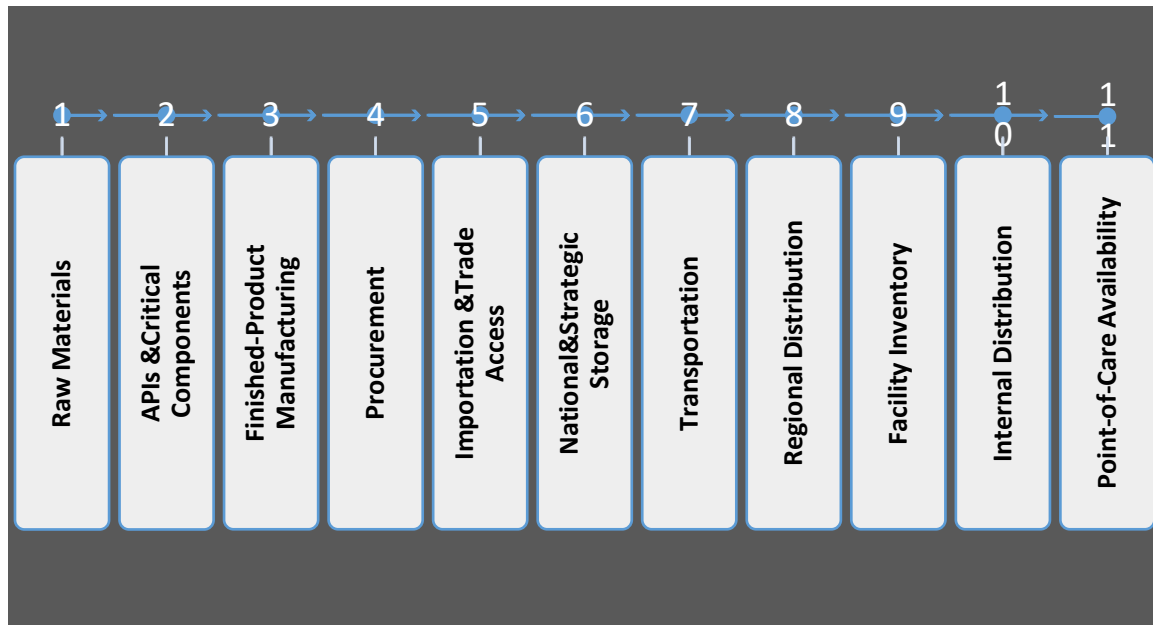
Table 4. Capacity States Identified Through Expert Interviews

Capacity State	Operational Definition
Nominal Capacity	Resources officially recorded as belonging to the health system
Available Capacity	Resources physically present and potentially available for use
Functional Capacity	Available resources capable of operating with necessary infrastructure, utilities, equipment, supplies and supporting inputs
Accessible Capacity	Functional resources that patients can physically and operationally reach
Effective Capacity	Functional and accessible capacity capable of providing the required service at the required time and level of care

Experts emphasized that deterioration could therefore remain partially hidden when monitoring relied primarily on conventional measures such as registered beds, facility numbers or installed equipment. The difference between nominal and effective capacity was identified as a particularly important marker of latent system vulnerability.

End-to-End Supply Chain Structure

Supply chain vulnerability emerged as a multistage process extending substantially beyond facility inventories and stock-outs. The expert analysis identified the following pathway:



Two broad categories of supplies were identified.

Health-specific supplies included medicines, vaccines, APIs, blood products, medical oxygen, laboratory reagents, medical devices, consumables and other clinical inputs. Critical non-health supplies included fuel, energy inputs, water, food, transportation inputs, spare parts, maintenance materials, communication-related resources and other supplies required to maintain healthcare operations. Experts emphasized that vulnerabilities could originate at any stage and subsequently propagate downstream. Table 5 shows Supply Chain Dependency Structure.

Table 5. Supply Chain Dependency Structure

Dependency Type	Operational Meaning
Raw-material dependency	Reliance on external or concentrated sources of essential starting materials
API/component dependency	Dependence on externally supplied APIs or critical components
Manufacturing dependency	Limited capacity to manufacture essential finished products
Supplier dependency	Reliance on one or a limited number of qualified suppliers
Geographic dependency	Concentration of supply within limited countries or regions
Import dependency	Reliance on imported finished products or manufacturing inputs
Route/corridor dependency	Dependence on limited ports, borders, maritime routes, roads or transportation corridors
Logistics dependency	Dependence on limited transport, storage or distribution capabilities
Inventory dependency	Insufficient buffer or strategic reserves to absorb disruption
Substitution dependency	Limited availability of alternative suppliers, products, inputs or routes

Two important distinctions emerged. First, domestic final production did not necessarily indicate supply independence when production depended on imported APIs, raw materials or components. Second, the existence of multiple suppliers did not necessarily indicate genuine diversification when suppliers depended on a common upstream producer, geographic source or transportation corridor.

Supply Chain Stages and Early Warning Points

Experts distinguished upstream vulnerability from downstream manifestations of supply failure. Table 6 shows Supply Chain Stages, Vulnerabilities, and Early Warning Signals.

Table 6. Supply Chain Stages, Vulnerabilities, and Early Warning Signals

Stage	Principal Vulnerability	Potential Early Warning Signal
Raw materials	Geographic/source concentration	Increasing concentration of critical input sources
API/components	External/single-source dependency	Increasing proportion dependent on limited API/component sources
Manufacturing	Limited/concentrated production capacity	Declining production; increasing capacity utilization
Procurement	Procurement delays or failures	Increasing procurement lead time; failed tenders; reduced supplier participation
Importation/trade	Border/import dependency	Increasing clearance time; import delays; declining import volume
Routes/corridors	Concentrated transportation pathways	Route disruption; declining availability of alternatives
Strategic storage	Insufficient reserve	Declining days of stock; increasing reserve drawdown
Transportation	Fuel, route or logistics constraints	Increasing delivery time; delayed/cancelled shipments
Regional distribution	Allocation/distribution bottlenecks	Increasing incomplete or delayed orders
Facility inventory	Accelerated depletion	Declining buffer stock; emergency purchasing
Internal distribution	Facility allocation problems	Increasing internal supply delays
Point of care	Final resource unavailability	Stock-outs, treatment delays and service interruption

This structure demonstrated that facility stock-outs represented relatively late manifestations of supply deterioration. Earlier signals could appear at sourcing, manufacturing, procurement, transportation or reserve levels before direct clinical consequences became evident.

Interdependencies and Cascading Failure Pathways

The expert interviews identified multiple mechanisms through which disruption in one component could affect several other components simultaneously. Electricity disruption could affect medical equipment, laboratories, refrigeration, oxygen systems, water provision, communications and other essential facility operations. Transportation disruption could simultaneously impair supply delivery, patient access, workforce mobility and referral pathways. Fuel shortages could affect generators, ambulances, logistics and distribution.

However, participants emphasized that deterioration was not necessarily linear. Several vulnerabilities could emerge simultaneously and reinforce one another. Consequently, the convergence of warning signals across interconnected domains was considered more important than the deterioration of a single indicator in isolation.

Early Warning Indicator Framework

Early warning indicators were classified according to system level, resource domain, SEA dimension, and stage of deterioration. **Table 7.** shows Core Early Warning Indicators and SEA Classification.

Table 7. Core Early Warning Indicators and SEA Classification

Level	Domain	Indicator	Measurement	SEA Dimension	Signal Stage
L1	Infrastructure	Reliability of critical national energy supply	Availability/interruption rate	Stability	Early Stress
L1	Infrastructure	Critical transport-route redundancy	No./% viable alternatives	Adaptability	Structural
L1	Supply Chain	Critical raw-material external dependency	%	Stability / Adaptability	Structural
L1	Supply Chain	API/component external dependency	%	Stability / Adaptability	Structural
L1	Supply Chain	Supplier concentration	No and share of suppliers	Stability / Adaptability	Structural
L1	Supply Chain	Geographic source concentration	No of zones	Stability / Adaptability	Structural
L1	Supply Chain	Critical-route/corridor dependency	critical routs / total routes	Stability / Adaptability	Structural
L1	Supply Chain	Strategic reserve coverage	Days	Stability / Adaptability	Early Stress
L2	Infrastructure	Health facilities with reliable essential utilities	%	Stability	Early Stress
L2	Capacity	National functional-to-nominal capacity ratio	%	Stability / Efficiency	Deterioration
L2	Capacity	National reserve/surge capacity	%	Adaptability	Structural/Early Stress
L2	Supply Chain	Procurement lead-time increases from baseline	%	Efficiency / Stability	Early Stress
L2	Supply Chain	Critical products with alternative suppliers	%	Adaptability	Structural
L3	Infrastructure	Regional alternative access-route availability	%	Adaptability / Stability	Structural
L3	Capacity	Regional functional capacity utilization	%	Efficiency / Stability	Early Stress
L3	Capacity	Referral/transport availability	% / response time	Stability / Efficiency	Early Stress

L3	Supply Chain	On-time and complete delivery	%	Efficiency / Stability	Early Stress
L3	Supply Chain	Regional stock coverage	Days	Stability / Adaptability	Early Stress
L4	Infrastructure	Facilities with functional backup power	%	Adaptability / Stability	Structural
L4	Infrastructure	Backup power autonomy	Hours/days	Adaptability	Early Stress
L4	Infrastructure	Critical equipment functionality	%	Stability / Efficiency	Deterioration
L4	Capacity	Functional-to-nominal facility capacity	%	Stability / Efficiency	Deterioration
L4	Capacity	Facility surge reserve	%	Adaptability	Early Stress
L4	Supply Chain	Critical-item buffer stock	Days	Stability / Adaptability	Early Stress
L4	Supply Chain	Emergency procurement frequency	Events/time	Efficiency / Stability	Deterioration
L5	Capacity	Effective-to-nominal capacity ratio	%	Stability / Efficiency	Advanced Deterioration
L5	Capacity	Essential service availability	%	Stability	Functional
L5	Supply Chain	Point-of-care critical-item availability	%	Stability / Efficiency	Advanced Deterioration
L5	Supply Chain	Critical-item stock-out duration	Hours/days	Stability	Functional
L5	Service Function	Essential service interruption due to infrastructure/capacity/supply failure	Frequency/duration	Stability	Functional Failure

3.9. Expert-Derived Risk Classification

Experts classified the identified indicators using five progressive risk states from safe to near collapse in 5 risk stage, increasing dependency, concentration, delay, interruption and utilization indicated increasing risk, whereas declining functionality, redundancy, reserve, accessibility and availability indicated deterioration. Table 8 shows Proposed Expert-Derived Risk Bands for Core Indicators.

Table 8. Proposed Expert-Derived Risk Bands for Core Indicators

Indicator	Safe	Emerging Vulnerability	High Risk	Critical	Near Collapse
Functional/nominal capacity ratio	≥90%	80–89%	70–79%	50–69%	<50%
Effective/nominal capacity ratio	≥90%	80–89%	70–79%	50–69%	<50%
Available surge/reserve capacity	>20%	15–20%	10–14%	5–9%	<5%
Strategic stock coverage for critical supplies	>90 days	61–90 days	31–60 days	15–30 days	<15 days
Facility critical-item buffer stock	>30 days	21–30 days	14–20 days	7–13 days	<7 days
Critical items dependent on single supplier/source	<10%	10–19%	20–34%	35–49%	≥50%
Critical raw-material/API external dependency	<20%	20–39%	40–59%	60–79%	≥80%
Critical supply dependent on dominant route/corridor	<20%	20–39%	40–59%	60–79%	≥80%
Critical products with viable alternative suppliers	>90%	75–90%	50–74%	25–49%	<25%
Critical flows with viable alternative routes	>90%	75–90%	50–74%	25–49%	<25%
Procurement lead-time increases from baseline	<10%	10–24%	25–49%	50–99%	≥100%
On-time and complete deliveries	≥95%	90–94%	80–89%	60–79%	<60%
Critical equipment operational	≥95%	90–94%	80–89%	60–79%	<60%
Facilities with functional backup power	≥95%	85–94%	70–84%	50–69%	<50%
Backup power autonomy	>7 days	4–7 days	2–3 days	12–47 h	<12 h
Point-of-care critical-item availability	≥98%	95–97%	90–94%	80–89%	<80%
Essential service availability	≥95%	90–94%	80–89%	60–79%	<60%

These ranges represented expert-derived operational thresholds for identifying progressive deterioration rather than universal normative standards. Participants emphasized that the interpretation of individual indicators should consider both persistence and interaction with other warning signals. A high structural dependency did not necessarily indicate imminent collapse when substantial reserves, redundancy and substitution capacity remained available. Conversely, simultaneous deterioration across several interconnected indicators could rapidly increase overall risk. The convergence of warning signals therefore emerged as an important component of system-level risk assessment.

Integration with the SEA Model

Following inductive identification of the five levels, vulnerabilities and indicators, the findings were classified according to the Stability–Efficiency–Adaptability (SEA) model. Stability represented the ability to maintain continuity and reliability of infrastructure, essential supplies and functional service capacity. Efficiency represented the ability to convert available infrastructure and resources into usable healthcare capacity through effective allocation, procurement, logistics, inventory management, distribution and utilization. Adaptability represented the ability to absorb disruption through redundancy, reserves, alternative suppliers, substitute products, alternative routes, backup infrastructure, surge capacity and service reconfiguration. Table 9 shows SEA Interpretation Across the Five-Level Framework.

Table 9. SEA Interpretation Across the Five-Level Framework

System Level	Stability	Efficiency	Adaptability
L1 National Critical Systems	Reliability of energy, water, transport, communications and critical supply flows	Effective use and movement of national resources	Diversified sourcing, alternative routes, strategic reserves and national backup capacity
L2 Health-System Level	Continuity of national healthcare and supply networks	Procurement, allocation and utilization of system capacity	Surge capacity, alternative suppliers and redistribution capability
L3 Regional/Distribution Level	Continuity of regional services and supply distribution	Efficient referral, logistics, storage and distribution	Alternative routes, redistribution and regional reserve capacity
L4 Facility Level	Continuous facility operation and resource availability	Conversion of installed resources into functional capacity	Backup utilities, facility reserves, substitution and surge capability
L5 Point of Care	Continuous availability of essential services and inputs	Effective conversion of resources into delivered care	Ability to substitute, reorganize or maintain essential care under disruption

The SEA analysis demonstrated an important dynamic pattern. Declining Stability did not immediately result in service failure when sufficient Adaptability remained available. Backup electricity, reserve stocks, alternative suppliers, alternative transportation routes and surge capacity could temporarily compensate for disruption. However, sustained pressure progressively consumed these adaptive buffers. Once reserves, redundancy and substitution capacity were depleted, declining Stability increasingly translated into loss of functional and effective capacity. Efficiency also deteriorated as increasingly scarce resources required emergency procurement, redistribution, substitution or rationing.

The analysis demonstrated that many of the earliest warning signals occurred upstream of conventional indicators of healthcare failure. Supplier and geographic concentration, raw-material and API dependency, route concentration, declining alternative capacity, increasing procurement lead times, reduced strategic reserves, decreasing backup autonomy and widening gaps between nominal and functional capacity could emerge before visible stock-outs or service interruptions.

The findings therefore suggest that infrastructure, capacity, and supply chain vulnerability should not be assessed solely through the physical quantity of assets, registered service capacity, or aggregate availability of commodities. Effective health system capacity depends on whether infrastructure and resources remain available, functional, accessible, continuously supplied, and sufficiently adaptable under pressure. Early warning indicators and their corresponding risk bands operate across these three dimensions, enabling deterioration to be detected before downstream manifestations such as persistent stock-outs, major capacity loss, service interruption, or functional collapse become dominant.

5. Discussion

This study suggests that infrastructure-related vulnerability in health systems cannot be adequately understood by examining healthcare facilities, equipment, or physical assets in isolation. The findings extend the concept of health infrastructure beyond the conventional boundaries of the health sector by demonstrating that healthcare delivery depends on a wider network of critical systems, operational capacities, and supply chains. Electricity, water, energy, transportation, communications, logistics, and access routes may exist outside the direct control of health authorities, yet their functionality can determine whether healthcare infrastructure remains operational. This provides the central rationale for moving **beyond health infrastructure** toward an integrated assessment of infrastructure, capacity, and supply chain dependencies.

A major implication of the findings is the distinction between the physical presence of resources and their actual contribution to healthcare delivery. Conventional capacity measures frequently describe the number of hospitals, beds, intensive care units, diagnostic facilities, or pieces of equipment available within a system. Such measures are important but may conceal deterioration when resources remain physically present while becoming partially or completely unusable. The progression identified in this study nominal, available, functional, accessible, and effective capacity suggests that the relevant measure for early warning is not simply how much capacity a system possesses, but how much of that capacity can actually deliver care under prevailing conditions. A widening gap between nominal and effective capacity may therefore signal deterioration before conventional capacity statistics reveal substantial change.

The five-level structure further demonstrates that health system vulnerability can originate considerably upstream of healthcare facilities. National energy systems, transportation networks, communication systems, production capabilities, trade routes, and strategic reserves influence health-system networks, regional distribution, facility operation, and ultimately point-of-care availability. This hierarchical relationship is important because a health system may retain intact

hospitals and clinical resources while losing functionality through failures occurring elsewhere in the supporting environment. Health system resilience therefore depends partly on systems over which health authorities may have limited direct control.

Supply chain findings reinforce this broader perspective. Shortages at healthcare facilities represent the visible endpoint of a much longer sequence extending from raw materials and critical components through manufacturing, procurement, importation, transportation, storage, distribution, and final point-of-care availability. Monitoring only stock-outs therefore identifies a relatively late stage of deterioration. Supplier concentration, geographic concentration, dependence on imported raw materials or APIs, increasing procurement lead times, declining strategic reserves, and reduced transportation alternatives may provide substantially earlier indications of emerging vulnerability.

The distinction between domestic production and supply-chain independence is particularly important. A health system may appear relatively self-sufficient because finished medicines or medical products are manufactured domestically while remaining dependent on imported raw materials, APIs, components, specialized equipment, or other production inputs. Similarly, apparent supplier diversification may provide limited protection when multiple suppliers ultimately depend on the same upstream manufacturer, geographic source, or transportation corridor. Assessment of supply resilience should therefore consider the depth and concentration of dependency across the entire chain rather than relying only on the location of final production or the number of immediate suppliers.

The same principle applies to non-medical inputs. Healthcare facilities require a continuous supply of electricity, water, fuel, food, transportation, communications, spare parts, maintenance inputs, and other resources. Failure of these supporting flows may produce clinical consequences even when medicines, equipment, and healthcare personnel remain available. Supply-chain surveillance should consequently extend beyond conventional pharmaceutical and medical-device inventories to encompass the non-health inputs necessary to maintain healthcare functionality.

Another important finding concerns **interdependency and cascading failure**. Infrastructure, capacity, and supply chains do not deteriorate independently. Disruption of electricity may simultaneously affect equipment, laboratories, refrigeration, oxygen-related systems, communications, and other essential operations. Transportation disruption may affect supply delivery, referral pathways, patient access, and workforce mobility. Fuel shortages may simultaneously compromise generators, ambulances, and logistics. The resulting risk therefore depends not only on the severity of individual disruptions but also on their capacity to propagate through interconnected systems.

This observation has implications for interpreting early warning indicators. A single structural vulnerability does not necessarily imply imminent system failure. High import dependency, for example, may remain manageable when supply routes are stable, strategic reserves are sufficient, suppliers are diversified, and substitution is feasible. The same dependency becomes substantially more dangerous when accompanied by route disruption, increasing procurement lead times, declining inventories, and limited alternatives. Consequently, convergence, persistence, and interaction of warning signals may provide more meaningful information about proximity to collapse than any isolated threshold.

The SEA analysis provides an additional explanation for why major disruptions do not always immediately produce health system failure. A decline in Stability can initially be compensated for through Adaptability. Backup power, alternative suppliers, strategic reserves, substitute products, alternative transport routes, redistribution of resources, and surge capacity can maintain essential functions despite disruption. However, these mechanisms represent finite adaptive buffers. Prolonged or repeated pressure can progressively consume reserves, redundancy, and substitution

options. Once adaptive capacity becomes depleted, instability increasingly translates into declining Efficiency, loss of functional capacity, saturation, and interruption of essential services.

This dynamic suggests that early warning systems should monitor not only the disruption itself but also the remaining capacity to compensate for disruption. The duration of backup power, days of strategic stock, number and viability of alternative suppliers, alternative transportation routes, remaining surge capacity, and ability to substitute critical resources may therefore be as important as measures of the primary disruption. Declining adaptive reserve may represent a transition point between a resilient system absorbing a shock and a fragile system approaching functional failure.

The proposed five-level framework provides a means of locating these warning signals across the system. At the national level, monitoring focuses on critical infrastructure, production, import dependency, strategic reserves, supplier concentration, and route redundancy. At the health-system and regional levels, procurement, allocation, referral, distribution, and surge capacity become increasingly important. At the facility level, the emphasis shifts toward operational infrastructure, backup systems, functional capacity, inventory, and critical equipment. At the point of care, the relevant outcome is whether the patient can actually access a functioning service with the necessary resources at the required time.

This progression also clarifies the distinction between early warning and failure measurement. Stock-outs, cancelled procedures, inaccessible services, and loss of essential care are important indicators, but they frequently describe deterioration after substantial protective capacity has already been lost. Indicators located further upstream such as increasing dependency concentration, reduced redundancy, longer procurement lead times, declining reserve coverage, reduced backup autonomy, and widening gaps between nominal and effective capacity may provide a longer intervention window.

The proposed risk continuum from Safe to Emerging Vulnerability, High Risk, Critical, and Near Collapse translates these indicators into an operational monitoring structure. However, the framework also suggests that risk classification should not rely mechanically on isolated thresholds. Indicator direction, persistence, interaction, and the availability of compensatory mechanisms should be considered together. A system with substantial structural dependency but strong reserves and redundancy may have a different short-term risk profile from a system with moderate dependency but rapidly deteriorating supplies and no viable alternatives.

Taken together, the findings suggest a shift in health system monitoring from an asset-based perspective to a functional dependency perspective. The central question is no longer simply whether infrastructure, beds, equipment, medicines, or supplies exist. Rather, assessment should determine whether the interconnected systems required to make those resources usable remain functional and whether sufficient redundancy exists to sustain them when disruption occurs. This perspective provides a basis for identifying vulnerabilities that may remain invisible to conventional performance measures until they have already translated into service failure.

The framework should nevertheless be interpreted as an early conceptual and operational model. The proposed indicators and expert-derived risk ranges require subsequent validation across different health systems and disruption contexts. The relative importance of individual indicators may differ according to geography, health system structure, domestic production capability, import dependency, infrastructure reliability, and exposure to conflict, disasters, economic shocks, or prolonged system pressure. Future empirical testing should therefore assess indicator sensitivity, threshold validity, interactions among indicators, and the potential development of a composite early warning index.

6. Conclusion

Health system infrastructure cannot be adequately assessed within the physical boundaries of healthcare facilities. The ability to maintain essential services depends on an interconnected network of healthcare infrastructure, critical external systems, usable capacity, and continuous medical and non-medical supply chains extending from national and upstream sources to the point of care.

This study integrates infrastructure, capacity, and supply chain within a five-level framework extending from national critical infrastructure and strategic systems through health-system and regional networks to healthcare facilities and patient-accessible care. The findings further distinguish nominal capacity from available, functional, accessible, and effective capacity, demonstrating that substantial deterioration may occur while conventional measures of physical capacity remain apparently unchanged.

Supply chain vulnerability similarly extends beyond facility stock-outs. Dependencies may originate in raw materials, APIs and components, manufacturing, suppliers, geographic concentration, importation, critical transportation corridors, storage, logistics, distribution, and non-medical inputs essential for healthcare operation. Monitoring these upstream dependencies provides an opportunity to identify deterioration before shortages and service interruption become evident.

Integration with the Stability–Efficiency–Adaptability (SEA) model further indicates that health systems may temporarily maintain functionality despite declining stability by using reserves, redundancy, substitution, backup systems, alternative routes, and surge capacity. Progressive depletion of these adaptive buffers represents a critical transition toward declining effective capacity, saturation, and functional failure.

The proposed early warning framework therefore shifts attention from what a health system possesses to what remains functional under pressure. Monitoring dependency, redundancy, supply continuity, adaptive reserves, and the gap between nominal and effective capacity across multiple system levels may enable earlier recognition of deterioration and provide decision-makers with additional time to intervene before disruption progresses to widespread failure or health system collapse.

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