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Structural fragility of installed capacity in an urban health-service network in Colombia through a multidimensional ecological study

Fragilidad estructural de la capacidad instalada en una red urbana de servicios de salud en Colombia mediante un estudio ecológico multidimensional

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SUMMARY

Objective: *To characterize the structural fragility of installed health-service capacity in Barranquilla, Atlántico, Colombia, using absolute capacity, supply concentration, reserve or transitory capacity, and service-line clinical sensitivity as structural-risk dimensions.* **Methods**: *An ecological health-services study was conducted using a local installed-capacity dataset traceable to the Colombian Special Registry of Health Service Providers and SISPRO, together with two contextual World Bank series for Colombia: physicians per 1,000 population and premature mortality from noncommunicable diseases. Traceable data cleaning, functional normalization, separation of baseline versus transitory capacity when allowed by the source fields, and exploratory estimation of a relative structural fragility proxy index using a normalized Poisson-type transformation were performed. This index was interpreted exclusively as a comparative structural-fragility ranking and not as an observed probability of saturation.* **Results**: *The analytical capacity of the Barranquilla node included 5,397 installed capacity slots. Adult ICU accounted for 707 slots and neonatal ICU for 160. Reserve capacity was low in the neonatal ICU (2.5%) and higher in the adult ICU (32.2%). The largest service lines were adult general hospitalization, adult ICU, and pediatric general hospitalization, whereas the highest relative structural fragility was observed in low-scale and highly concentrated services, including burn care, acute mental health, and highly specialized lines selected.* **Conclusion**: *Barranquilla has a broad but markedly heterogeneous structural health-service capacity network. The critical pattern is not determined only by the absolute number of slots, but by the interaction between limited capacity, high concentration, low stable reserve, and clinical sensitivity. The evidence generated is structural and should not be interpreted as observed occupancy, real-time saturation, or operational collapse.*

Keywords: *Installed capacity, structural fragility, Barranquilla, REPS, concentration, Herfindahl-Hirschman Index, mental health, pediatric intensive care, neonatal intensive care, public health*

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RESUMEN

Objetivo*: Caracterizar la fragilidad estructural de la capacidad instalada de los servicios de salud en Barranquilla, Atlántico, Colombia, utilizando la capacidad absoluta, la concentración de la oferta, la capacidad de reserva o transitoria y la sensibilidad clínica de las líneas de servicio como dimensiones de riesgo estructural.* **Métodos***: Se realizó un estudio ecológico de servicios de salud utilizando un conjunto de datos locales de capacidad instalada, trazable al Registro Especial de Proveedores de Servicios de Salud de Colombia y al SISPRO, junto con dos series contextuales del Banco Mundial para Colombia: médicos por cada 1000 habitantes y mortalidad prematura por enfermedades no transmisibles. Se llevó a cabo la limpieza de datos trazables, la normalización funcional, la separación de la capacidad de referencia frente a la transitoria cuando lo permitían los campos de origen, y la estimación exploratoria de un índice proxy de fragilidad estructural relativa mediante una transformación normalizada de tipo Poisson. Este índice se interpretó exclusivamente como una clasificación comparativa de la fragilidad estructural y no como una probabilidad observada de saturación.* **Resultados***: La capacidad analítica del nodo de Barranquilla incluyó 5397 espacios de capacidad instalada. La UCI para adultos contaba con 707 plazas y la UCI neonatal con 160. La capacidad de reserva era baja en la UCI neonatal (2,5%) y mayor en la UCI para adultos (32,2 %). Las líneas de servicio más grandes fueron hospitalización general para adultos, UCI para adultos y hospitalización general pediátrica, mientras que la mayor fragilidad estructural relativa se observó en servicios de baja escala y alta concentración, como la atención de quemaduras, la salud mental aguda y las líneas altamente especializadas seleccionadas.* **Conclusión***: Barranquilla posee una red de servicios de salud con amplia capacidad estructural, pero marcadamente heterogénea. El patrón crítico no se determina únicamente por el número absoluto de plazas, sino por la interacción entre la capacidad limitada, la alta concentración, la baja reserva estable y la sensibilidad clínica. La evidencia generada es estructural y no debe interpretarse como ocupación observada, saturación en tiempo real ni colapso operativo.*

Palabras clave: *Capacidad instalada, fragilidad estructural; Barranquilla, REPS, concentración, Índice de Herfindahl-Hirschman, salud mental, cuidados intensivos pediátricos, cuidados intensivos neonatales, salud pública*

INTRODUCTION

Assessing hospital sufficiency in complex urban systems cannot rely solely on crude counts of beds or service slots. Recent literature has shown that health-system resilience depends on the interaction between physical capacity, effective staffing, territorial distribution, provider concentration, the possibility of transitory expansion, and the type of service involved (7-19). In particular, hospital occupancy is best understood as a complementary indicator of system pressure; however, its interpretation requires information on capacity, flows, and operational availability. Therefore, international thresholds, including the frequently cited 85% alert threshold, should be considered referential and not equivalent to real-world performance (8-10,14).

This clarification is particularly important for clinically sensitive services such as pediatric critical care, mental health, acute psychiatry, neonatal intensive care, and burn units. In these lines, a small number of slots may appear acceptable in absolute terms but become structurally fragile when supply is concentrated in a few providers or when expansion depends on transitory mechanisms (11,12,17,20-24). In practice, structural fragility emerges when a service line combines low scale, high concentration, and limited stable response capacity. The objective of this study was to develop a critical reading of installed capacity in Barranquilla as a provider node within Atlántico, without assuming that the city represents the entire department. The study also sought to improve methodological traceability by specifying extraction platforms, data-cleaning procedures, functional normalization, the distinction between baseline and transitory capacity, and the analytical framework used to derive a relative structural fragility proxy index, explicitly acknowledging that real occupancy was not available and that an exact probability of saturation could not be estimated. The contribution of this study lies in integrating volume, concentration, reserve, and clinical sensitivity to identify potentially vulnerable lines even when the aggregate volume of service slots appears broad.

METHODS

Design and setting

An ecological and descriptive-analytical study of installed health-service capacity was conducted. The primary setting was Barranquilla, analyzed as a provider node within Atlántico. The analysis did not use data from other departments and did not assume that Barranquilla was equivalent to the departmental total. The design relied on administrative installed-capacity sources and country-level macro indicators for contextualization, not for direct local inference.

Data sources and extraction platforms

The main source was a local installed-capacity file by provider/site, traceable to the Colombian Special Registry of Health Service Providers (REPS) and the SISPRO repository "Services and installed capacity of health-care institutions by department or district and legal nature" (1,2). As a macro-context, two World Bank World Development Indicators CSV files were used: physicians per 1,000 people (SH.MED.PHYS.ZS) and premature mortality from cardiovascular disease, cancer, diabetes, or chronic respiratory disease between ages 30 and 70 (SH.DYN.NCOM.ZS) (3-6). Table 1 summarizes the platforms, analyzed files, analytical units, and role of each source. To strengthen regulatory traceability and national context, recent Ministry of Health documents related to REPS, service availability, and sectoral management frameworks were also reviewed (25-29).

Cleaning, normalization, and variable construction

Data cleaning followed previously audited and traceable rules. Negative values were excluded from the analysis. Missing values would only be considered zero if the field represented capacity slots and the record explicitly indicated that the service did not apply; this condition was not observed in the final dataset. Duplicates by provider-site were flagged in a quality log and were not resolved by simple inference. A normalization dictionary was subsequently built to avoid double counting across functionally equivalent service labels, for example, conventional adult ICU and adult ICU "3100". Consolidation used a conservative row-level rule (the maximum value across equivalent labels) to avoid overestimating supply.

Capacity was distinguished as baseline versus reserve/transitory only when the field name explicitly declared this distinction. When the file structure did not allow separation of baseline and transitory capacity, the line was analyzed as total capacity. Services were additionally grouped into clinical macroblocks (adult general/critical/observation, neonatal, pediatric, mental health/psychiatry, addictions/substance use, obstetric, burn care, and other services) to synthesize fragility patterns at a functional scale.

Table 1. Extraction platforms, analyzed files, and role of each source

Platform	Analyzed file	Analytical unit	Analytical role
SISPRO / REPS	Local extract 'CAPACIDAD_INSTALADA_EN_BARRANQUILLA_20260228.xlsx'	Provider-site and capacity lines	Main source: tracer installed supply
World Bank DataBank / WDI	WB_WDI_SH_MED_PHYS_ZS.csv	Colombia, annual series	Macro-context for medical workforce
World Bank DataBank / WDI	WB_GS_SH_DYN_NCOM_ZS.csv	Colombia, annual series	Macro-context for premature NCD mortality

The local source was treated as an administrative extract traceable to REPS/SISPRO; the World Bank series were used only to contextualize the local analysis

Structural indicators

Four main dimensions were calculated: (1) absolute capacity by service line; (2) supply concentration, using the leading provider share, the cumulative share of the top three providers, and the Herfindahl-Hirschman Index (HHI); (3) reserve availability, expressed as the percentage of transitory slots over total capacity; and (4) clinical sensitivity, defined a priori to penalize lines in which delay or operational closure could generate more severe consequences, including pediatric ICU, neonatal ICU, acute mental health, psychiatry, and burn care (Table 2) (11,12,20-24).

Relative structural fragility proxy index

Because information on real occupancy, average length of stay, bed turnover, functional closures, staffing by shift, and temporal referral/counter-referral flows was unavailable, no observational probability of saturation was estimated. Instead, a relative proxy index of structural fragility was constructed for exploration and comparative purposes across service lines. The index integrated four predefined dimensions: lower effective capacity, greater supply concentration, greater dependence on reserve/transitory capacity, and higher clinical sensitivity. Concentration was represented through the Herfindahl-Hirschman Index and the cumulative share of the top three providers. Clinical sensitivity was assigned qualitatively a priori, penalizing lines in which delay, functional closure, or low redundancy could have more severe clinical consequences, such as neonatal ICU, pediatric ICU, acute mental health, psychiatry, and burn care (11,12,20-24).

To express results on a common scale, a normalized Poisson-type transformation was used, in which the parameter λ increased when low capacity, high concentration, reserve dependence, and greater clinical sensitivity coincided. The transformation $p = 1 - \exp(-\lambda)$ was used exclusively as a comparative scaling mechanism. Therefore, the resulting values should not be interpreted as a real probability of saturation, operational collapse, expected occupancy, or individual clinical risk. Their usefulness is limited to structurally ranking service lines within the analyzed set. The fragility traffic-light classification was defined by terciles of the service-line distribution: low, medium, and high relative structural fragility (Table 3).

RESULTS

The normalized dataset consolidated 35 functional service lines and a total installed analytical capacity of 5,397 slots. The network showed a strongly adult-centered profile: adult general hospitalization (2,163 slots) and adult ICU (707 slots) dominated installed capacity, whereas neonatal ICU contributed 160 slots and pediatric general hospitalization contributed 355 slots. These relationships are summarized in Table 2 and visualized in Figure 1.

However, volume-based reading alone was not sufficient to identify relative structural fragility. When capacity was examined together with concentration, small but critically exposed services emerged. Figure 2 shows a particularly sensitive quadrant in the low-capacity and high-HHI segment, where adult and pediatric burn ICU, acute mental care, pediatric mental health, and selected highly specialized lines were located. Table 3 presents the 10 service lines with the highest relative structural fragility proxy index.

Lines classified with a high signal should not be interpreted as currently saturated services, but as lines with greater relative structural fragility within the analyzed set. Descriptively, these lines shared three patterns: low-capacity scale, high concentration among providers, and greater clinical sensitivity. Operational interpretation of these findings requires additional information on real occupancy, staffing availability, referral flows, functional closures, and timeliness of access.

Reserve availability was not distributed homogeneously. Reserve dependence was very low in the neonatal ICU (2.5%) and considerably higher in the adult ICU (32.2%), suggesting that

Table 2. Top 10 service lines by total installed capacity

Service line	Total slots	Providers with capacity	% reserve	HHI	Concentration
Adult General Hospitalization	2163	47	0.0	538	Low
Adult ICU	707	31	0.3	511	Low
Pediatric General Hospitalization	355	23	0.1	585	Low
Adult Intermediate Care	248	30	0.2	641	Low
Obstetrics	206	10	0.0	1224	Low
Adult Observation – Women	192	20	0.0	676	Low
Neonatal ICU	160	16	0.0	1004	Low
Adult Observation – Men	149	20	0.0	627	Low
Adult Substance Use Care	141	5	0.0	2133	Moderate
Neonatal Intermediate Care	113	17	0.0	731	Low

The table shows that the largest structural volume is concentrated in adult general hospitalization, adult ICU, and pediatric general hospitalization

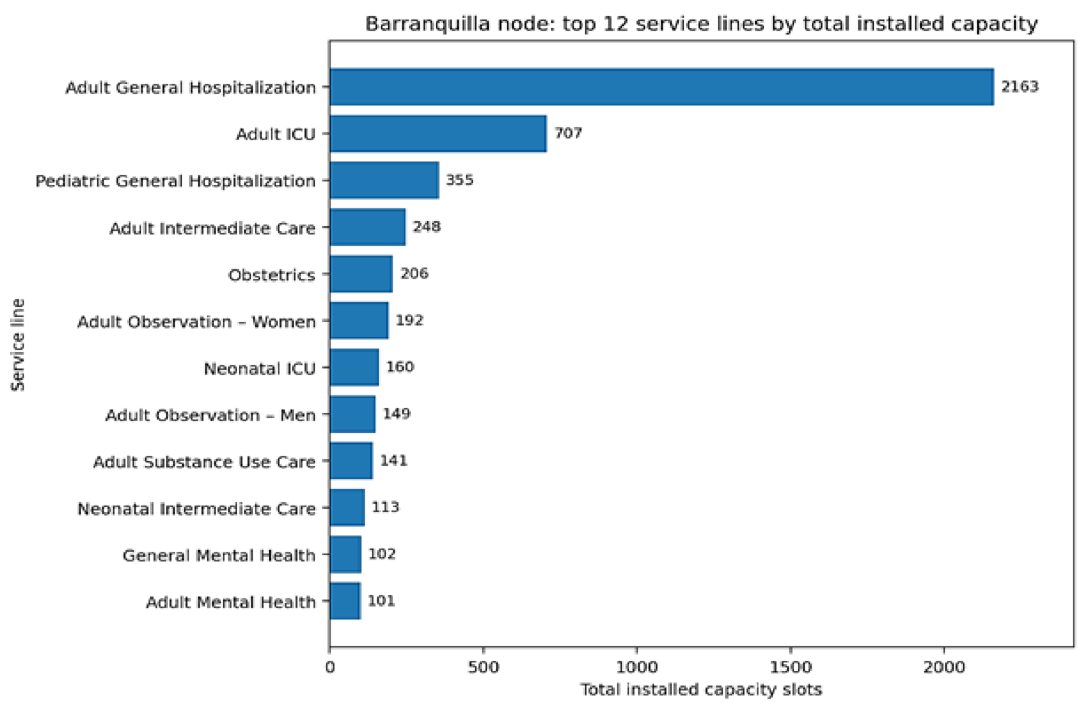

Figure 1. Barranquilla node: top 12 service lines by total installed capacity. The horizontal bar chart shows the predominance of adult service lines and the structural weight of adult ICU within the node

part of adult slack may depend on slots that are not necessarily stable. This pattern is relevant because a high physical ceiling can overestimate resilience when the permanent base is comparatively smaller. Additionally, 19 lines showed high HHI (>2,500), a finding compatible with structural dependence on few providers even within a sizeable network.

At the macroblock level, the largest volume was observed in adult general/critical/observation services, followed by pediatric and neonatal

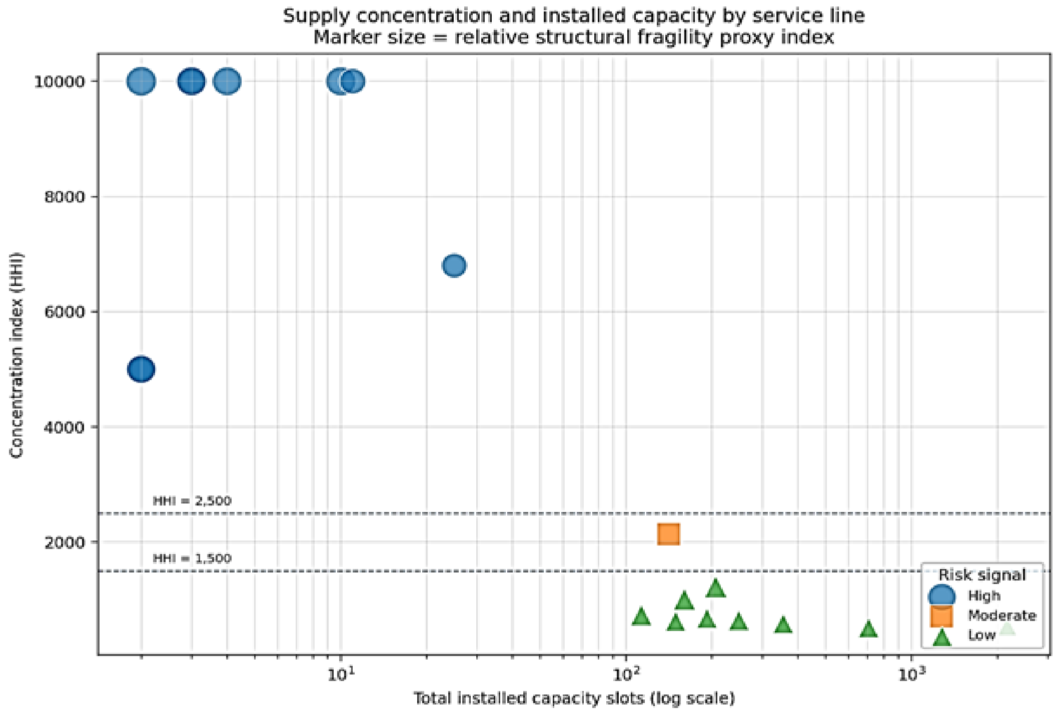

Figure 2. Concentration versus capacity (marker size = a proxy for relative structural fragility). Each marker represents a service line. Marker size increases with the relative structural fragility proxy index, and the marker type/color follows the traffic-light signal

Table 3. Service lines with the highest relative structural fragility proxy index

Service line	Macroblock	Total slots	% reserve	HHI	Top 3 (%)	Proxy index	Signal
Adult Burn ICU	Burn care	2	0.0	5000	100.0	0.367	High
Pediatric Burn ICU	Burn care	3	0.0	10000	100.0	0.353	High
Acute Mental Care	Mental health/Psychiatry	2	0.0	10000	100.0	0.349	High
TPR	Other	10	100.0	10000	100.0	0.331	High
Pediatric Mental Health	Mental health/Psychiatry	3	0.0	10000	100.0	0.326	High
Adult General Observation	Adult general/critical/ observation	4	100.0	10000	100.0	0.326	High
Adult Burn Care	Burn care	2	0.0	5000	100.0	0.310	High
Pediatric Burn Care	Burn care	2	0.0	5000	100.0	0.310	High
Hematopoietic Progenitor Transplantation	Other high-complexity/ support	11	0.0	10000	100.0	0.248	High
Mental Health Stretchers	Mental health/Psychiatry	25	0.0	6800	100.0	0.222	High

The ranking integrates capacity, concentration, reserve, and clinical sensitivity; it does not represent real occupancy or observed saturation services. However, the highest mean proxy index shifted toward mental health/psychiatry and burn care, reflecting the combined influence of lower scale and concentration. Table 4 summarizes this synthesis and Figure 3 facilitates comparison across clinical macroblocks.

DISCUSSION

The central finding of this study is that structural fragility of installed capacity does not necessarily coincide with the highest absolute volume of service slots. In apparently broad urban

Table 4. Service lines with the highest relative structural fragility proxy index

Macroblock	N lines	Total slots	Median HHI	Median % reserve	Mean proxy index
Adult general/critical/observation	6	3463	634	12.5	0.161
Pediatric general/critical/observation	4	536	1021	0.7	0.166
Neonatal	3	341	830	0.0	0.157
Mental health/Psychiatry	6	327	5935	0.0	0.234
Addictions/Substance use	5	321	4688	0.0	0.192
Obstetric/Perinatal	2	271	1972	0.0	0.160
Chronic/Long-stay care	3	108	2837	0.0	0.198
Other high-complexity/support	1	11	10000	0.0	0.248
Other	1	10	10000	100.0	0.331
Burn care	4	9	5000	0.0	0.335

The ranking integrates capacity, concentration, reserve, and clinical sensitivity; it does not represent real occupancy or observed saturation

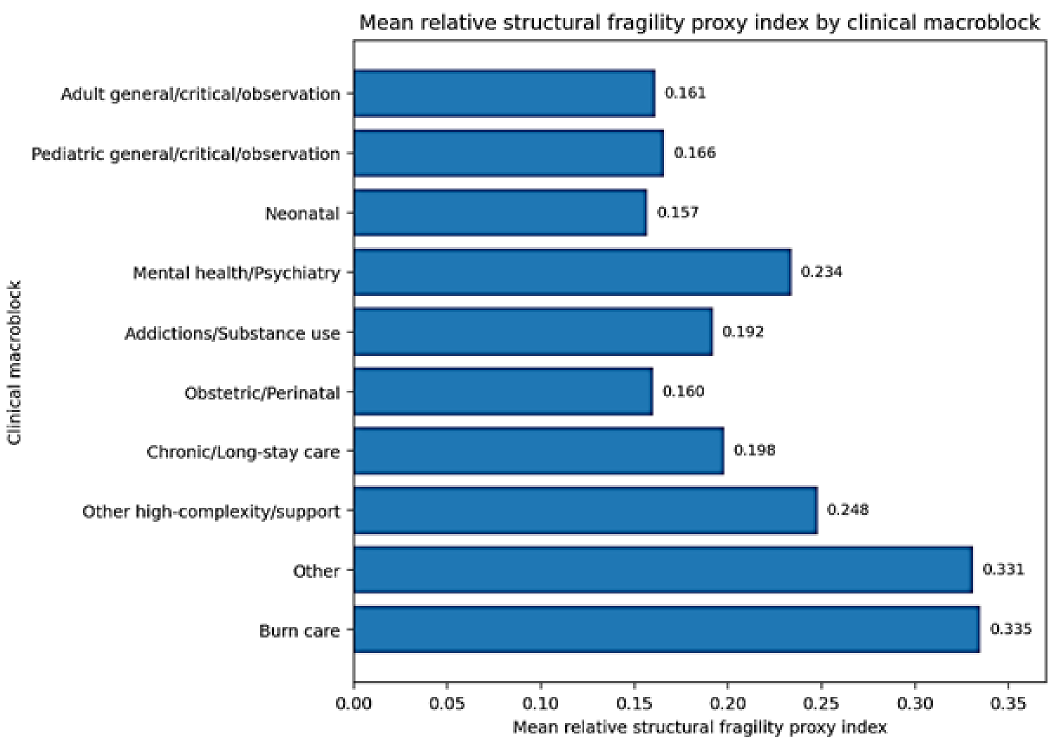

Figure 3. Mean relative structural fragility proxy index by clinical macroblock. Mental health/psychiatry and burn care show greater relative structural exposure despite their lower absolute volume

networks, structural sufficiency should be assessed not only by the aggregate magnitude of supply but also by its functional distribution, concentration among providers, reserve stability, and the clinical sensitivity of each service line. This approach does not allow claims about observed saturation or real operational performance; however, it does identify lines with greater relative structural vulnerability that should be prioritized in surveillance, planning, and sufficiency analysis.

The results also suggest that concentration is an insufficiently incorporated dimension in local discussions of installed capacity. High HHIs in multiple lines indicate that operational continuity of certain services may depend on very few providers. From a public-health perspective, this implies greater vulnerability to closures, financial crises, supply shortages, workforce constraints, or contractual reconfigurations. International evidence on pediatric critical care and respiratory surge management supports the importance of considering not only how many beds exist but also where they are located, how much load they absorb, and how balanced their distribution is (20-24).

Another relevant finding was the difference between baseline and transitory capacity. The neonatal ICU showed a relatively stable structure, whereas the adult ICU depended more heavily on reserve capacity. This contrast does not permit inference to saturation, but it does modulate the interpretation of sufficiency. A service with more total slots may be less resilient than one with fewer slots if much of its expansion relies on contingent mechanisms. This distinction is consistent with contemporary hospital resilience frameworks that emphasize real, rather than merely nominal, redundancy (16-19).

The analysis benefited from a more explicit methodology for traceability and cleaning. Identification of negative values, duplicates, nominal equivalences, and transitory capacity helped avoid double-counting bias and structural optimism. In addition, explicit mention of SISPRO/REPS and World Bank DataBank extraction platforms improves reproducibility and allows other groups to replicate or extend the approach in other cities (1-6,25-29).

The main strength of the study is the integration of data-quality auditing, clinical normalization, structural modeling, and advanced visualization into a single analytical workflow. Another strength is the use of recent references and official platforms to anchor methodological interpretation and sectoral discussion. However, the limitations are substantive. First, the study did not include actual occupancy, average length of stay, bed turnover, functional closures, shift-by-shift staffing, or referral/counter-referral flows. Second, the unit of analysis was structural and administrative; therefore, the results cannot be used to infer the timeliness of access, quality of care, operational continuity, or clinical outcomes. Third, the relative structural fragility proxy index was designed as an exploratory tool for internal ranking and not as a validated predictive model. Consequently, the findings should be interpreted as a mapping of relative structural fragility rather than as evidence of observed saturation, real operational deficit, or service collapse.

CONCLUSIONS

Barranquilla presents a broad yet heterogeneous structural network of installed health service capacity. Relative fragility is not necessarily concentrated in the lines with the largest number of slots, but in those that combine low scale, high concentration, limited stable slack, and high clinical sensitivity. Acute mental health, burn care, and selected pediatric and specialized lines require priority structural surveillance. These findings should not be interpreted as evidence of saturation, but rather as an analytical signal to guide health planning, sufficiency monitoring, the reduction of excessive dependence on a few providers, and the strengthening of clinically sensitive services. Future studies should integrate real occupancy, temporal flows, workforce availability, and clinical outcomes to move from structural fragility mapping toward operational risk assessment.

DECLARATIONS

- **Ethics and consent**: This study used secondary administrative data on installed capacity and did not include identifiable patient data or intervention on human participants; therefore, individual informed consent did not apply.

- **Data and code availability**: Derived analytical files, including Excel sheets, JSONL files, and HTML visualizations, may be shared as supplementary material and/or upon reasonable request to the corresponding author.

- **Conflicts of interest**: The authors declare no conflicts of interest related to the content, analysis, or interpretation of the results of this study.

- **Use of artificial intelligence**: Computational assistance was used to support editorial organization, textual cleaning, and manuscript structuring. Study conception, interpretation of results, critical review, final approval, and responsibility for the content remain exclusively with the human authors.

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