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Original Article

A system dynamics model applied to administrative variables influencing hospital length of stay in the neonatal intensive care unit (NICU)

Modelo de dinámica de sistemas aplicado a variables administrativas en la estancia hospitalaria en UCIN

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Abstract

Introduction: in Colombia, the high occupancy rates of Neonatal Intensive Care Units (NICUs)—86.6% in public institutions and 80.3% in private ones—have highlighted the need to improve care processes in these units.
Objective: to develop a tool to represent and analyze the factors affecting hospital length of stay (LOS) in a third-level hospital in Bogotá.
Methodology: based on the characterization of the care process, carried out through semi-structured interviews and direct observation, a simulation model was developed to explore different scenarios by varying key parameters. Three simulation scenarios were defined, incorporating neonatal mortality indicators and crude birth rates, stratified across three geographical scales: global population estimates, Latin America and the Caribbean, and national data from Colombia.
Results: the results indicate that administrative and technological management factors, particularly interinstitutional referrals, authorization processes, response times for corrective maintenance, and the availability of biomedical equipment, exert a systemic influence on NICU operational performance and LOS.
Conclusions: the findings highlight the need for integrated improvement strategies that align clinical care with administrative coordination, technological management, and knowledge transfer, promoting more efficient use of resources, reducing hospital length of stay, and improving neonatal outcomes.

Keywords: Systems dynamics, Hospital stay, management, maintenance NICU

Resumen

Introducción: en Colombia, las altas tasas de ocupación de las Unidades de Cuidados Intensivos Neonatales (UCIN) —86,6% en instituciones públicas y 80,3% en privadas— han puesto de relieve la necesidad de mejorar los procesos de atención en estas unidades.
Objetivo: desarrollar una herramienta para representar y analizar los factores que afectan la duración de la estancia hospitalaria (DHL) en un hospital de tercer nivel de Bogotá.
Metodología: a partir de la caracterización del proceso de atención, realizada mediante entrevistas semiestructuradas y observación directa, se construyó un modelo de simulación que permite explorar diferentes escenarios mediante la variación de parámetros clave. Se definieron tres escenarios de simulación que incorporan indicadores de mortalidad neonatal y tasas brutas de natalidad, estratificados en tres escalas geográficas: estimaciones de población mundial, América Latina y el Caribe, y datos nacionales de Colombia.
Resultados: los resultados indican que los factores de gestión administrativa y tecnológica, en particular las derivaciones interinstitucionales, los procesos de autorización, los tiempos de respuesta para el mantenimiento correctivo y la disponibilidad de equipos biomédicos, ejercen una influencia sistémica en el rendimiento operativo de la UCIN y la DHL.
Conclusiones: los hallazgos resaltan la necesidad de estrategias de mejora integradas que alineen la atención clínica con la coordinación administrativa, la gestión tecnológica y la transferencia de conocimientos, lo que favorece un uso más eficiente de los recursos, la reducción de la estancia hospitalaria y la mejora de los resultados neonatales.

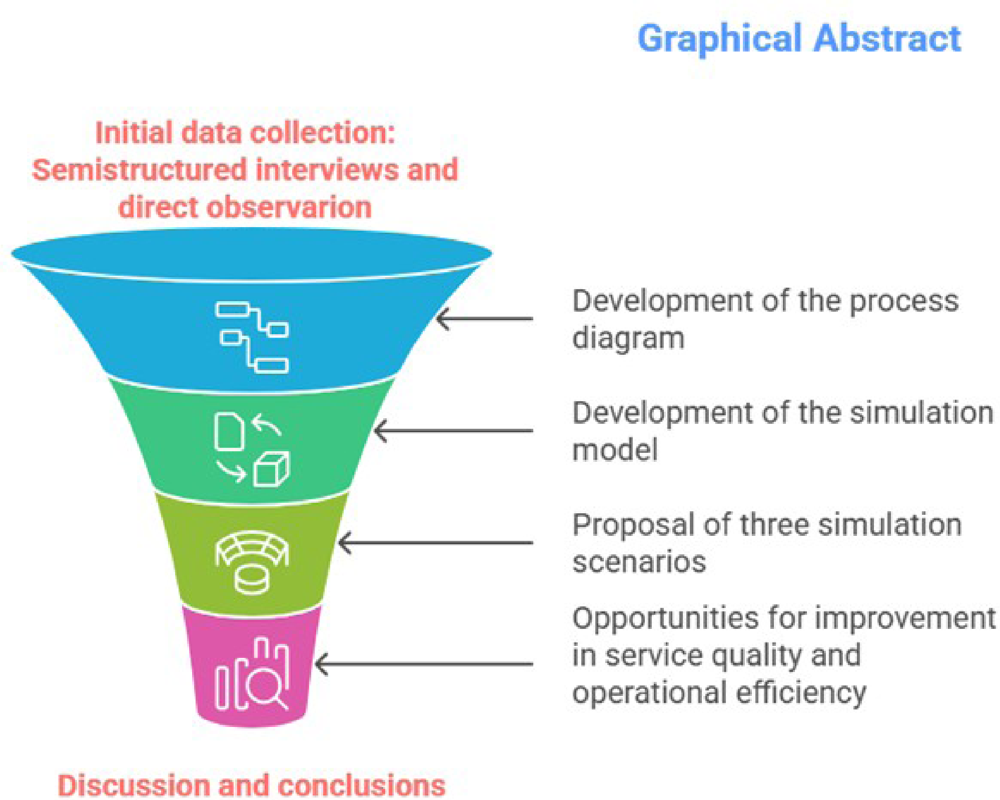
Palabras clave: Dinámica de sistemas, Estancia Hospitalaria, Gestión hospitalaria, mantenimiento UCIN, Capacidad hospitalaria

Contribution to the literature:
This study provides a systems-based analysis of hospital length of stay in NICUs, highlighting the systemic influence of administrative and technological management factors beyond clinical care.

The most relevant results include:
Identification of inter-institutional referrals, authorization processes, and biomedical equipment management as key determinants affecting NICU operational efficiency and hospital stay.

These results contribute to the following:
Evidence to support integrated improvement strategies that align clinical, administrative, and technological processes to optimize NICU performance and neonatal outcomes.

Graphical Abstract



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Introduction

The neonate refers to a newborn during the first 28 days of life. During this period, vital physiological and biological processes develop, indicating the organism's adaptation from the intrauterine environment to the outside world. The immaturity of the newborn's immune system and the limited functional capacity of its systems make it particularly vulnerable to infections, diseases, and clinical complications (1). They can be categorized as Neonates (born between 37 and 42 weeks of gestation), Premature Neonates (born before 37 weeks), and Post-term Neonates (born after 42 weeks),(1).

In areas with overpopulation and low or middle income levels, limitations in infrastructure, human resources, and technology directly affect the quality of healthcare and neonatal outcomes, (2). A recent report by the World Health Organization (WHO) states that about 15 million premature births happen worldwide each year. It is estimated that over half of the deaths linked to this condition could be prevented with timely and proper care in Neonatal Intensive Care Units (NICUs), (1,3). Perinatal and neonatal mortality rates in Latin America and the Caribbean are higher among children born to women with lower educational levels and incomes (4). However, progress has been made in decreasing neonatal mortality. High occupancy rates and resource shortages remain major challenges in NICUs, highlighting the urgent need to enhance operational and management processes in these units, (5).

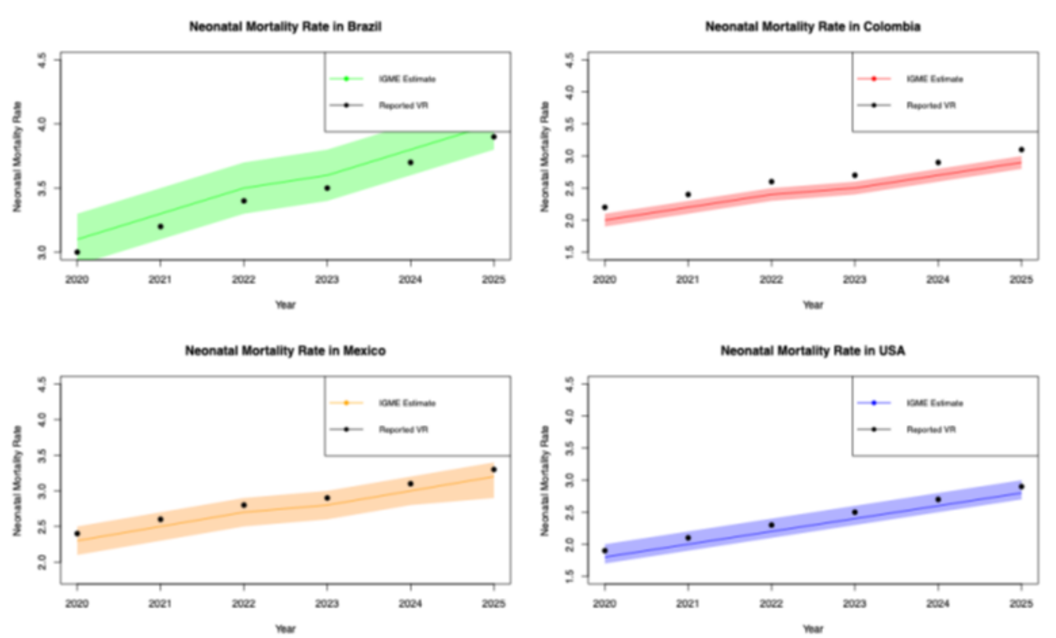

Figure 1 IGME Estimate and Reported Values Brazil, Colombia, Mexico and USA (6).

Figure 1 compares Neonatal Mortality Rate (NMR) trends for Brazil (green), Colombia (red), Mexico (orange) and the United States (blue) from 2020 to 2025. The data comes from the United Nations Inter-Agency Group on Child Mortality Estimation research and the Child and Adolescent Causes of Death Estimation Project, (6). Accurate quantification of preterm birth prevalence remains difficult due to underreporting in many countries, especially those with lower incomes, but an increasing trend in the overall preterm birth rate has been observed.

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Although data show a stabilization in comparative rates, the WHO and UNICEF have highlighted significant progress, especially in improving neonatal care and implementing public health policies. However, gaps in equitable access to health services still exist (3). Having studies that support the adaptation of health policies to meet each country's specific needs is essential to continue making progress in reducing neonatal mortality.

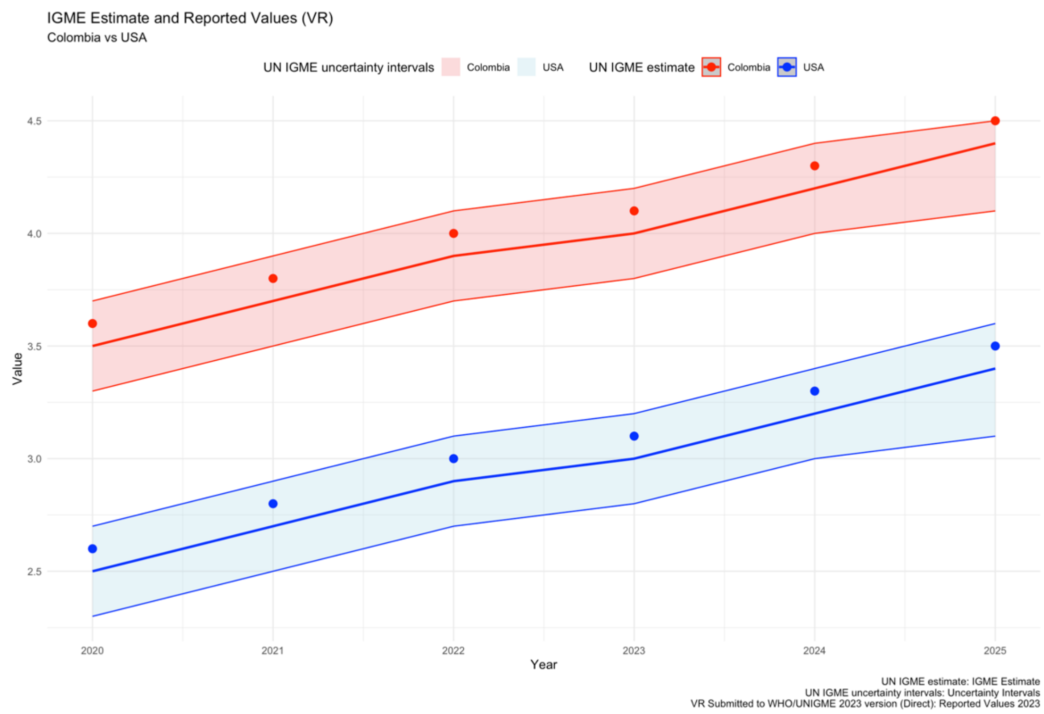

Figure 2 IGME Estimate and Reported Values Colombia vs USA (6)

Figure 2 compares neonatal mortality rate trends between the United States and Colombia; the blue and red lines represent the United Nations Inter-Agency Group on Population and Population Change (IGME) estimates for both countries, respectively, while the shaded areas (light blue for Colombia and light red for the U.S.) show the uncertainty intervals tied to those estimates, indicating the range where the true value is likely to fall. The black dots show the reported values (RV) for each country, reflecting the available data for that period.

NICUs are essential for caring for high-risk newborns, and their status varies widely around the world. In high-income countries, NICUs set standards for biomedical equipment, staff training, and protocols that help lower neonatal mortality. However, even in these settings, workforce challenges persist, affecting clinical care, neonatal nursing education, and research, and creating significant obstacles, (7).

In Colombia, NICUs are under increasing pressure due to the high occupancy rate (86.6% in public institutions and 80.3% in the private sector), (8). This overload, along with the complexity of neonatal care processes, has emphasized the need to analyze operations and enhance the quality of care provided (9). In this context, efficient resource management, reducing HS times, minimizing errors, and avoiding reprocessing have become priorities in the health sector.

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Materials and Methods

The study adopted a mixed-methods design and was conducted in a high-complexity public healthcare institution in Bogotá, Colombia, between June and November 2023. The neonatal care process was initially characterized using semi-structured interviews, direct observation, and a review of procedures performed in the NICU, covering the entire continuum from pre-admission to patient discharge. Based on this information, a process flowchart was developed to represent the care pathway.

The interview sample was stratified, including healthcare professionals from the NICU, administrative staff from the billing and referral/counter-referral departments, and personnel from the biomedical engineering department of the institution. All participants provided written informed consent before participating. The study protocol was reviewed and approved by the institution’s Ethics Committee (Approval File No 05-2023).

The interviews were guided by a predefined list of factors, which participants were asked to rank based on how often they perceived these occurring in the NICU, according to their professional experience. These factors included: affiliation regime within the Colombian Health System, settlement processes at discharge, authorization procedures by insurers, referrals to other institutions or services, authorizations for home delivery of medical supplies, receipt and delivery of paraclinical test results, intra-hospital patient transfers, corrective and preventive maintenance activities, training in the use of home medical devices, lack of backup biomedical equipment, and inter-service technology provision. Participants could exclude factors they found not applicable and suggest additional factors not included in the original list.

Based on the care process flowchart, a causal diagram was developed, followed by a system dynamics simulation to assess the effects of key parameters such as reductions in corrective maintenance and increases in installed capacity. Specifically, Stella Architect software (www.iseesystems.com) was used.

Retrospective quantitative data were gathered from the patient’s medical records. Study variables included demand, installed capacity, Biomedical Equipment Availability, clinical laboratory and diagnostic imaging, and healthcare utilization during hospitalization stay.

Retrospective quantitative data for 2022 were gathered from patient medical records and the biomedical engineering department databases. The study variables included patient demand, installed technological capacity, availability of biomedical equipment, access to clinical laboratory and diagnostic imaging services, and healthcare service use during hospitalization.

Finally, a sensitivity analysis was performed to assess the impact of installed capacity, mortality rate, referral rate, and the number of corrective maintenance operations.

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Results

Analysis of Interviews and Direct Observations

To characterize the care process, 26 stratified interviews were conducted, involving a total population of 48 individuals (N), (10). Among them, 22 were clinical staff, comprising three pediatricians, one head of the kangaroo care program, and two physical therapists. The remaining 16 were nursing staff, composed of 12 head nurses and four nursing assistants. Additionally, three administrative staff members were included, as well as one personnel member from the biomedical engineering department.

Table 1 presents the analysis of the responses obtained from clinical staff, highlighting key variables such as referral to other institutions, authorizations for home delivery of materials, and authorizations for procedures by insurers, which were identified as determinants of prolonged HS. The analysis consisted of counting the relevant variables for each individual and assigning a score to each response. The responses were multiplied by the assigned index to measure each variable's relevance, and the results were averaged to identify the most significant variables.

Table 1. Analysis of interview responses provided by NICU clinical staff. Source: The authors.

Determinant of Hospital Stay	1	2	3	4	5	6	7	8	Weighted average	Average
Affiliation regime to the Colombian Health System	15	1	1	1	3	0	1	0	46	5.75
Settlement at the time of discharge	8	1	2	4	3	2	1	1	74	9.25
Process authorizations by insurer	5	2	3	2	2	2	2	4	94	11.75
Referrals to other institutions or services	1	0	0	1	4	4	1	11	144	18.00
Authorizations for home delivery of materials	1	1	4	1	3	9	3	0	109	13.63
Receiving and delivering paraclinical results	16	3	1	0	1	1	0	0	36	4.50
Intra-hospital transfers	18	0	0	0	2	0	2	0	42	5.25
Corrective or preventive maintenance	15	4	1	0	0	0	1	1	41	5.13
Training in the use of home devices	15	1	4	0	1	1	0	0	40	5.00
Lack of backup biomedical equipment	14	4	1	0	0	3	0	0	43	5.38
Provision of technology between services	15	3	2	0	1	0	1	0	39	4.88

By analyzing the average values of the staff responses in Table 1, we can establish that the institution's greatest influence on the determinants of EH is referrals to other institutions or services (18.00), authorizations for home delivery of materials (13.63), authorizations for processes by the

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insurer (11.75), and settlement at the time of discharge (9.25). We can establish that the processes in the administrative areas need to be reviewed, as they are causing delays in EH. This is an alarm to verify compliance with the institution's policies and mission, as indicators are affected by issues outside the institution's CORE in the provision of health services.

Through direct observation of NICU processes, the subprocesses with the greatest impact on hospital length of stay were identified as patient referrals to other facilities for transfers or additional procedures, requests for outsourced corrective maintenance, and authorization of services by the insurance company. Table 2 provides a detailed analysis of the times associated with each of these subprocesses.

Table 2. Durations of subprocesses based on direct observation. Source: The authors.

Subprocesses	**Total duration**	**Clinical aspect (minutes)**	**Administrative aspect (minutes)**
Patient admission	50 minutes	30	20
Daily evolution	6 – 7 minutes	6 - 7	-
Nursing assistant care process	1 - 7 minutes	1 - 7	-
Referral of patient to another institution due to transfer	1 week - several months	-	-
Referral of a patient to another institution for examination or clinical procedure.	1 week - several months	-	-
Taking clinical laboratory tests	5 - 8 minutes	5 - 8	-
Getting diagnostic imaging tests	6 – 11 minutes	6 - 11	-
Request for supplies, biomedical equipment, and medications from the NICU	10 – 15 minutes	11	4
Request for corrective maintenance of biomedical equipment	1 hour – 1 day (response)	6 – 7 (request)	-
Request for authorization or referral to the patient's insurance.	1 day - several weeks (depending on the insurer)	-	-
Patient discharge and clinical and administrative clearance	60 minutes	30	30
Kangaroo Program	20 – 45 minutes	20 - 45	-

Regarding biomedical equipment, although most devices were operational, 29% had exceeded their expected useful life and required frequent corrective maintenance, resulting in disproportionate costs relative to their current market value. In addition, the analysis identified opportunities to optimize maintenance management through outsourcing, which could reduce equipment downtime and achieve an average response time of approximately 1 day.

However, prioritizing in-house management of biomedical technology would enable greater control over repair turnaround times, spare parts availability, and the organization and utilization of physical space within the NICU.

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Model in system dynamics

Based on the characterization of the neonatal care process, the causal diagram (Figure 3) was developed to show the dynamic interaction among available resources, clinical care, and patient status, illustrating how system interventions can produce reinforcing (positive) or balancing (negative) effects, (11). The diagram is read by following the connections between variables along the direction of the arrows; when an arrow has a + sign, it indicates that the two variables are directly related, (12–14). The neonatal care process is described through variable relationships: a positive sign (+) indicates a direct relationship, while a negative sign (–) indicates an inverse one (15–18).

Patient admission flow is constrained by the interaction of stochastic arrival demand and deterministic infrastructure capacity. Installed capacity represents the maximum number of simultaneously available incubators, limited by preventive and corrective maintenance regimes. When demand exceeds available capacity, excess demand accumulates in an admission queue (non-admitted patients stock). Hospitalized patient population drives implementation of the Kangaroo Mother Care Program (a clinical protocol centered on parent-infant dyadic interaction and continuous contact) which operationalizes three discharge pathways stratified by clinical complexity: (1) discharge for recovered patients achieving clinical stability, (2) referral to lower-complexity services for patients requiring ongoing but non-intensive care, and (3) referral to higher-complexity institutions for patients requiring tertiary interventions. These dynamics are governed by two feedback loops:

Loop B1: Loop B1 (Capacity Constraint): Patient hospitalization occupies incubators, reducing available capacity. Increased hospitalized patient population directly constrains admission capacity for new patients through automatic capacity depletion.

Loop B2: Kangaroo Program implementation enables accelerated discharge through clinical categorization and differentiated routing. Increased hospitalized census drives authorization for discharge eligibility assessment; successful completion of Kangaroo criteria enables movement through discharge pathways, thereby liberating incubator capacity for subsequent admissions. This mechanism constitutes a balancing loop in which high patient census indirectly reduces future census through accelerated discharge processing. Table 3 presents the description of the main variables of the causal diagram.

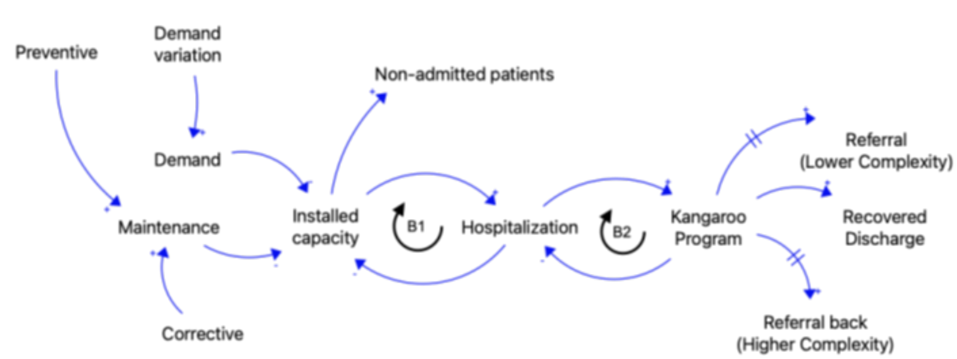

Figure 3. Causal diagram of the NICU care system. Source: The authors.

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Table 3. Main variables of the causal diagram. Source: The authors.

Variable	**Description**	**Representation in the model or initial value**
Demand	Patients who are admitted to the NICU	Poisson distribution of the NICU data, in simulation time units of days. The function used in STELLA® generates a series of random numbers that fit a Poisson distribution.
Installed Capacity	The number of biomedical equipment, specifically the NICU incubators, was considered.	32
Admission	Total history number of neonates admitted to the NICU per month, operationalized as hourly Poisson process. Includes 14 patients carried forward from prior period as initial condition.	Installed capacity-Demand in the previous period: 14 Admission per month: January=27, February=31, March=37, April=28, May=36, June=43, July=39, August=25, September=29, October=30, November=33 and December=21.
Biomedical Equipment Availability	The number of immediately available incubators within the NICU, accounting for maintenance-related unavailability and representing the operative ceiling for concurrent patient occupancy.	Biomedical equipment available in the previous period- $Biomedical\ Equipment(t) = Biomedical\ Equipment(t_o) + \int_0^t Installed\ Capacity\ (t_o) + \ dt$ $Biomedical\ Equipment(t) = Biomedical\ Equipment(t_o) + \int_0^t Installed\ Capacity\ (t_o) + \ dt$ $Installed\ Capacity(t) = Installed\ Capacity(t-dt) + (F_{output} - F_{Incubator} - F_{input} - F_{BE_{growth}})dt$ Where: $F_{BE_{growth}} F_{BE_{growth}}$: Biomedical Equipment Growth Flow F_{output}:F_{output}: Outflow $F_{Incubator}$:$F_{Incubator}$: Incubator flow F_{input}:F_{input}: Input flow

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Clinical Laboratory and Diagnostic Imaging	This variable pertains to medical procedures that enable healthcare professionals to assess a patient’s health, specifically through diagnostic imaging and clinical laboratory tests.	
Daily Process	This variable pertains to the routine and systematic assessment of the health status and progress of newborn patients in the unit.	Empirical distribution based on NICU data, on simulation days. Table 2.
Medication and Follow-up	This variable pertains to the application of pharmacotherapeutic intervention in patients.	
Admitted Patient	This refers to patients already admitted to the service. These are patients who require highly complex medical care, often in critical condition.	
Stable Patient	This variable refers to neonatal patients who no longer need highly specialized intensive care, such as that provided in a NICU.	Its function is to conceptually explore all relevant cause and effect relationships within the system, even those that do not translate directly into levels, flows or equations in the formal model.
Nursing Care Physical Therapy Care	This variable refers to a specific set of interventions and care provided by NICU nursing and physical therapy staff to ensure the well-being of newborns.	Empirical distribution based on NICU data, on simulation days. Table 2.
Kangaroo Program	It describes a neonatal care practice mainly aimed at fostering bonding between the newborn and their parents or caregivers. Without this process, the patient cannot be discharged from the NICU.	Empirical distribution based on NICU data, on simulation days. Table 2.
Referral (Lower Complexity) and Refereral back (Higher Complexity)	It describes the referral process, which is the transfer of a patient from a less complex unit to a more complex one, and the counter-referral process, which is the transfer of a patient from a more complex unit to a less complex one.	A rate of 0.52% was reported based on information from the highly complex public health institution in Bogotá in 2022.

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Recovered Dischange	Patients have completed their treatment in the service and have successfully overcome their critical medical condition.	A rate of 96.5% was reported based on information from the highly complex public health institution in Bogotá.
Dischange due to death	This variable relates to patients admitted to the NICU who died in the unit due to various critical conditions.	A rate of 3.15% was reported based on information from the highly complex public health institution in Bogotá.

Base scenario

Maintenance performance was characterized using historical data obtained from the hospital's maintenance department. Figure 4 presents the temporal evolution of four interrelated operational variables over a twelve-month simulation period: the number of hospitalized patients (pink line), installed bed capacity (blue line), corrective and preventive maintenance activities performed on biomedical equipment (purple line), and patient discharges (green line).

This multivariate representation enables a quantitative assessment of interactions among patient census, resource availability, and maintenance scheduling in a real neonatal intensive care unit setting. The trajectory of maintenance activities shows marked temporal clustering, indicating that corrective and preventive interventions are unevenly distributed throughout the simulation horizon. Notably, periods of high patient occupancy tend to overlap with increased maintenance activity, revealing operational misalignments that generate resource competition and workflow bottlenecks. These dynamics are associated with constraints on both maintenance execution and patient discharge processes.

By jointly visualizing these coupled variables, Figure 4 highlights how misaligned maintenance scheduling during peak occupancy periods may contribute to extended lengths of stay and reduced service throughput efficiency.

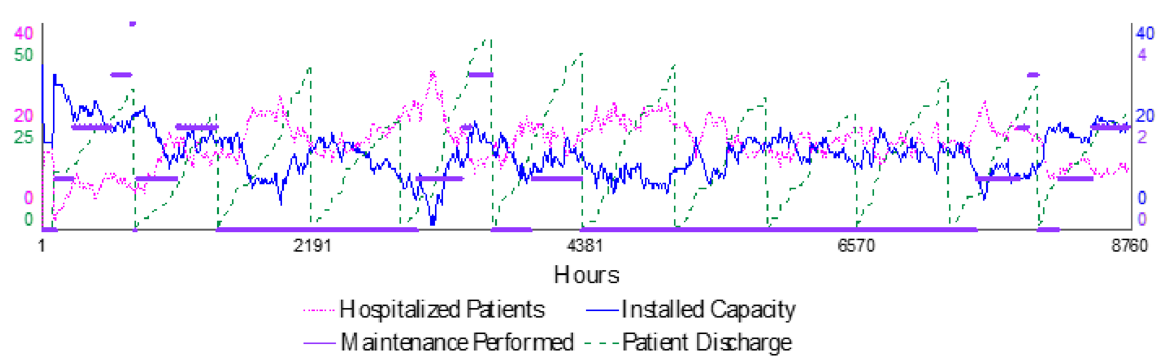

Figure 4. Dynamics of hospitalized patients, installed capacity, maintenance activities, and patient discharges, base scenario. Source: The authors.

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The simulation model was validated using correlation analysis conducted in Minitab. Monthly patient admission data from the study hospital were first compared with the corresponding simulation outputs, yielding a correlation coefficient of 0.989, which indicates a high level of agreement and an accurate representation of patient inflow dynamics. A comparable analysis was performed for monthly patient discharges, resulting in a correlation coefficient of 0.643. This lower correlation may be attributed to the presence of patients who remained hospitalized at the end of the simulation horizon, thereby influencing the discharge counts.

To further assess model performance, a paired Wilcoxon test was applied to compare observed values with model-generated results. The obtained p-values (0.154 and 0.516) exceeded the significance threshold of 0.05, indicating no statistically significant differences between empirical data and model predictions. In addition, correlation analysis between observed corrective maintenance activities and model estimates produced a coefficient of 0.951, reflecting a very strong positive association.

To evaluate the operational robustness of the NICU system in heterogeneous epidemiological contexts, three simulation scenarios were established. Each scenario incorporates neonatal mortality rates and crude birth rate indicators stratified across three geographic scales: global population estimates, Latin America and the Caribbean, and national data from Colombia (Table 4), based on the data available for 2023 in (19–21).The three scenario configurations (referred to as pessimistic, intermediate, and optimistic) represent trajectories that reflect the different levels of performance of the neonatal health system and the demographic transition. It is essential that the structural operational parameters remain unchanged in all scenarios to isolate the epidemiological effects of infrastructure-dependent variables: the installed incubator capacity remains constant at 32 units, the patient population remaining from the previous operating cycle remains fixed at 14 patients, institutional referral protocols persist at 0.52%, and the definitions of the patient recovery rate remain constant at 96.5%.

Corrective maintenance of biomedical equipment also remains uniform at five interventions per year across all scenarios. However, incubator maintenance intensity was adjusted across scenarios: the annual frequency of corrective maintenance was calibrated to 13 events in the base case, 0 in the pessimistic scenario, 16 in the intermediate scenario (50% of installed capacity), and 64 in the optimistic scenario (twice the installed capacity). This characterization of the degree to which variations in mortality and birth rates (holding operational constraints constant) in the resulting dataset provides empirical evidence on the contribution of epidemiological factors to the performance differences observed when institutional capacity remains structurally fixed.

Table 4 shows the variable parameters used in each scenario to assess the model's performance under various assumptions in Birth Rate, patient discharge protocols and corrective maintenance intensity in incubators.

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Table 4. Parameters given for sensitivity analysis. Source: The authors.

Simulation variables	Base scenario	Values		
		Pessimistic	Intermediate	Optimistic
Patient admission	395	448	437	423
Birth rate *1000	0%	15%	11%	7%
Patient discharges	3.15%	15%	13.5%	11%
Installed Capacity (Incubators)	32	32	32	32
Patients from the previous year	14	14	14	14
Referral rate	0.52%	0.52%	0.52%	0.52%
Recovery rate	96.5%	96.5%	96.5%	96.5%
Corrective maintenance in incubators	13	0	16	64
Corrective maintenance of Biomedical Equipment	5	5	5	5

Pessimistic scenario

The pessimistic scenario represents an operationally constrained environment characterized by elevated epidemiological demand and less resource availability. Results demonstrate a differential between the base scenario and pessimistic configuration: annual patient admissions increased from 395 to 448 patients (+13.4%), reflecting heightened neonatal demand stemming from birth rate amplification. Correspondingly, successful patient recoveries declined marginally from 355 to 351 patients (-1.1%), indicating that treatment efficacy was preserved despite operational constraints. However, mortality was the most sensitive outcome variable, escalating from 13 deaths (3.2% mortality rate) in the base scenario to 62 deaths (15.1% mortality rate) in the pessimistic scenario, a 376% absolute increase (49 additional deaths), representing a critical performance degradation. The residual patient population (those remaining in the system at simulation termination) increased from 27 to 35 patients (+29.6%), indicating system congestion and an obstruction of the discharge pathway. Bed utilization efficiency, measured as a utilization rate, deteriorated substantially, increasing from 1.41 under the base scenario to 2.06 in the pessimistic scenario (a 46% rise), indicating severe resource over-allocation and capacity saturation relative to the available infrastructure. The recovery rate declined from 0.968 to 0.848 (-12.4%), reflecting compromised therapeutic success under resource scarcity, while the mortality rate increased from 0.032 to 0.151 (+371 %). This comparative analysis quantifies the operational fragility of the NICU system: even moderate parameter variations (implemented through birth rate amplification and maintenance burden escalation) produce cascading performance degradation characterized by mortality escalation, reduced therapeutic efficacy, and persistent patient queuing. The results are shown in Table 5, substantiating the hypothesis that administrative and technical constraints constitute binding operational bottlenecks that amplify clinical consequences under stress conditions.

Intermediate Scenario

The comparative analysis between the base scenario and the intermediate configuration reveals performance degradation patterns of intermediate severity, demonstrating the NICU system’s response characteristics under operational stress. Annual patient admissions increased from 395 to 437 (+10.6%), indicating elevated neonatal demand driven by birth rate amplification, though

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less severely than in pessimistic conditions. Successful patient recoveries declined from 355 to 347 patients (-2.3%), reflecting a marginal reduction in therapeutic efficacy under moderate operational constraints. Mortality emerged as the critical outcome variable, escalating from 13 deaths (3.2% baseline mortality rate) to 55 deceased patients (12.6% mortality rate), an absolute increase of 42 fatalities representing a 323% relative mortality increase, indicating substantial clinical deterioration at intermediate operational stress levels. The residual patient population increased from 27 to 35 patients (+29.6%), matching the pessimistic scenario, demonstrating that administrative discharge bottlenecks persist regardless of the maintenance intensity parameterization. Bed utilization efficiency deteriorated from 1.41 (base) to 1.68 (intermediate) (a 19.1% increase) indicating moderate capacity saturation and resource strain. Recovery rate declined from 0.968 to 0.857 (-11.4%), reflecting compromised therapeutic success under moderate resource constraints, while mortality rate escalated from 0.032 to 0.142 a 344% relative increase. The intermediate scenario establishes a critical operational threshold: mortality amplification (323% increase) occurs disproportionately to the demand increase (10.6% increase), revealing non-linear system behavior in which modest epidemiological variations trigger a cascading escalation of mortality. This finding substantiates the hypothesis that NICU systems operate within a narrow operational envelope characterized by extreme sensitivity to perturbations in birth rate dynamics and maintenance burden, with mortality as the most reactive clinical indicator of system degradation. The trajectory from base to intermediate to pessimistic scenarios (mortality: 3.2%, 12.6%, 15.1%) demonstrates accelerating clinical consequences as operational parameterization worsens.

Optimistic scenario

The comparative analysis between the base scenario and optimistic configuration shows the maximum operational capacity achievable through system- level interventions and resource optimization. Annual patient admissions rose slightly from 395 to 423 (+ 7. 1%), reflecting a controlled increase in neonatal demand due to higher birth rates, while still remaining below pessimistic and intermediate levels. Successful patient recoveries slightly decreased from 355 to 345 (-2. 2.8%), indicating a minor reduction in therapeutic effectiveness despite optimized resource conditions, which suggests that increased demand somewhat hampers treatment success even under favorable operation settings. Importantly, mortality increased from 13 deaths (3. 3.2% baseline rate) to 42 deaths (11. 4% mortality rate), a rise of 29 fatalities representing a 223% increase, showing that even optimized operations cannot prevent significant mortality increases when epidemiological demand rises due to higher birth rates. The remaining patient population grew from 27 to 36 (+ 33. 3%), the highest across all three scenarios, revealing an unexpected result: better resource availability does not necessarily reduce discharge delays, indicating that administrative bottlenecks are structural issues resistant to resource improvements. Bed utilization efficiency worsened from 1. 41 (base) to 2. 06 (optimistic), matching the pessimistic scenario, suggesting that bed saturation mainly results from epidemiological demand rather than resource limitations, as both optimal and constrained systems reach similar capacity saturation levels. The recovery rate dropped from 0. 968 to 0. 886 (-8. 8.5%), showing a moderate decline in therapeutic success, while the mortality rate increased from 0. 032 to 0. 114, a 256% relative rise. The optimistic scenario reveals a key operational insight: mortality increases across all demand levels (pessimistic: + 376%, intermediate: + 323%, optimistic: + 223%), with all scenarios merging toward similar bed

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utilization saturation (range 1. 68-2. 06), indicating that higher epidemiological demand creates resilient operational pressures that persist despite resource optimization. This challenges the idea that merely increasing resources can solve capacity limits and shows that administrative discharge pathways (not infrastructure deficiencies) are the main system barriers during high epidemiological demand.

Table 5. Sensitivity analysis. Source: The authors

	Base scenario	Pessimistic	Intermediate	Optimistic
Patient admission	395	448	437	423
Recovered	355	351	347	345
Deceased	13	62	55	42
Patients in the system	27	35	35	36
Bed Utilization rate	1.41	2.06	1.68	2.06
Recovery Rate	0.968	0.848	0.857	0.886
Mortality Rate	0.032	0.151	0.142	0.114

Discussion

This study identified key administrative factors affecting HS, such as referrals to other institutions or services, approvals for home delivery of supplies, insurance authorizations, and discharge payments. These processes heavily depend on insurance approval and can delay care by weeks or even months. This poses a critical issue that healthcare systems need to regulate and monitor to reduce negative impacts on institutional capacity and financial sustainability. Research, (22), indicates that shorter HS promote stronger bonds between infants and their caregivers at home. They also reduce exposure to hospital settings and may lessen stress and financial strain for families balancing work or caring for others while visiting the NICU.

Regarding the impact of health insurance type, a recognized factor in this study, the literature showed a difference in the HS by insurer in unadjusted analyses, (23). Other important findings indicated that preterm infants with public insurance had fewer complications documented on hospital discharge records than those with private insurance, although this difference was not statistically significant. The reasons why preterm infants with public health insurance have fewer complications at the same gestational age, birth weight, and delivery method as infants with private insurance are unknown; however, this is an aspect that should be further studied.

Several studies have examined factors associated with prolonged HS in newborns, focusing mainly on clinical predictors such as birth weight, gestational age, and neonatal complications, as well as demographic characteristics (24–26). In contrast, the literature addressing administrative factors—despite their potential influence on length of stay—remains scarce. From a systemic and comprehensive perspective, strategies to enhance the quality of neonatal care have also emphasized strengthening healthcare infrastructure; specifically, expanding and optimizing NICUs and modernizing biomedical equipment have been identified as key factors in improving care processes and outcomes. (27). This aligns with the findings of this study, indicating that equipment modernization could improve patient safety, reduce repair times, and increase capacity availability, thereby leading to higher revenue.

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This study analyzed factors identified through the experiences of NICU healthcare professionals, administrative staff, and biomedical engineering personnel. Future research should examine additional factors—such as the distance between the family's home and the hospital, as well as parental experience—and assess their impact on prolonged HS, as reported in previous studies, (28).

The system dynamics simulation model showed high accuracy (coefficients >0.6 and up to 0.96 for admissions/discharges; p>0.05 in Wilcoxon test), confirming its reliability for NICU planning and continuous improvement. Validation in other hospital settings and cost-benefit analyses under pessimistic, intermediate, and optimistic scenarios are recommended to establish sustainable strategies.

The simulation scenarios demonstrated that the neonatal care system analyzed is highly vulnerable to failure under conditions of increased patient demand, whether gradual or sudden. In contrast, scenarios with lower demand showed greater system stability. Periods of high demand adversely affected patient recovery, mortality rates, and bed utilization. These findings highlight the need for administrative and logistical adjustments throughout the care delivery process to better manage demand fluctuations.

Conclusions

The survey results highlighted that the determinants of HE was referrals to other institutions or services, authorizations for processes, and authorizations for home delivery of materials. These require us to review the administration and management issues related to service provision because they are not part of the CORE of the healthcare provider institution. The other determinants of HE can be reviewed because they are close to the average of approximately 5; therefore, small changes can be made to these determinants, improving the perception of service quality.

In the subprocesses, it can be established that delays persist in administrative processes such as patient referrals to another institution for transfer and patient referrals to another institution for examination or clinical procedure. However, we can observe that there is significant opportunity for improvement in requests for corrective maintenance of medical equipment, which can take from 1 hour to 1 day. From a biomedical engineering perspective, we can review the processes for training technical staff, backing up medical equipment, and the number of technical staff in the engineering department.

Findings demonstrate that administrative variables related to technological management (corrective maintenance, biomedical equipment availability) and inter-institutional processes (communication during staff rotation, coordination with insurers) exert systemic influence on NICU operational efficiency, suggesting that continuous improvement strategies must integrate technical, administrative, and knowledge management components to optimize hospital length of stay and improve neonatal outcomes. These results provide actionable insights for healthcare administrators and policymakers seeking to enhance neonatal care delivery through systems-based approaches, contributing to the growing body of evidence supporting the application of system dynamics modeling in healthcare management and quality improvement initiatives.

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