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DOI
10.1136/bmjopen-2025-104688

Publication date
2025

Document Version
Final published version

Published in
BMJ Open

BMJ Open

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To cite: Wagenaar JHL, Dietz A, Huang Y, *et al*. Impact assessment of neonatal care interventions on regional neonatal care capacity: a simulation study based on clinical data in the Netherlands. *BMJ Open* 2025;**15**:e104688. doi:10.1136/bmjopen-2025-104688

► Prepublication history and additional supplemental material for this paper are available online. To view these files, please visit the journal online (https://doi.org/10.1136/bmjopen-2025-104688).

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Received 06 May 2025
Accepted 13 November 2025

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ABSTRACT

Objective To analyse the impact of selected neonatal care interventions on regional care capacity.

Design
Discrete event simulation modelling based on clinical data.

Setting Neonatal care in the southwest of the Netherlands, consisting of one tertiary-level neonatal intensive care unit (NICU), four hospitals with high-care neonatal (HCN) wards and six with medium-care neonatal (MCN) wards.

Participants 44 461 neonates admitted to at least one hospital within the specified region or admitted outside of the region but with a residential address inside the region between 2016 and 2021.

Interventions The impact of three interventions was simulated: (1) home-based phototherapy for hyperbilirubinaemia, (2) oral antibiotic switch for culture-negative early onset infection and (3) changing tertiary-level NICU admission guidelines.

Main outcome measure Regional neonatal capacity defined as: (1) occupancy per ward level, (2) required operational beds per ward level to provide care to all inside region patients at maximum 85% occupancy, (3) proportion rejected, defined as outside region transfers due to no capacity to provide local care and (4) the weekly rejections in relation to occupancy to provide a combined analysis.

Results In the current situation, with many operational beds closed due to nurse shortages, occupancy was extremely high at the NICU and HCNs (respectively 91.7% (95% CI 91.4 to 92.0) and 98.1% (95% CI 98.0 to 98.2)). The number of required beds exceeded available beds, resulting in >20% rejections for both NICU and HCN patients. Although the three interventions individually demonstrated effect on capacity, clinical impact was marginal. In combination, NICU occupancy was reduced below the 85% government recommendation at the cost of an increased burden for HCNs, highlighting the need for redistribution to MCNs.

Conclusion Our model confirmed the severity of current neonatal capacity strain and demonstrated the potential impact of three interventions on regional capacity. The model showed to be a low-cost and easy-to-use method for regional capacity impact assessment and could provide the basis for making informed decisions for other interventions and future scenarios, supporting data-driven neonatal capacity planning and policy development.

STRENGTHS AND LIMITATIONS OF THIS STUDY

⇒ We developed a discrete event simulation model incorporating comprehensive clinical data from 48 180 neonatal admissions spanning multiple hospitals, enhancing the precision and relevance of the simulation outcomes.
⇒ The model explicitly captures interhospital transfer dynamics across three levels of neonatal care (neonatal intensive care unit, high-care neonatal and medium-care neonatal), providing a realistic representation of regional care complexity.
⇒ The open-source nature of the model promotes transparency, reproducibility and facilitates adaptation and validation in comparable neonatal care settings.
⇒ Assumptions of stable patient arrival rates and not allowing for overflow beds throughout the simulation period might underestimate the impact of short-term fluctuations or unexpected demographic shifts.
⇒ The simulation model focused on neonatal wards and currently does not include interacting hospital settings, such as paediatric and obstetric wards.

INTRODUCTION

Hospital capacity strain is an urgent and growing problem in neonatal care for many high-income countries, such as the Netherlands. The Dutch government expects a shortage of 266 000 healthcare workers over the next 10 years, an increase from 3.3% to almost 16% shortage.[1 2] This burden could compromise the quality of care for neonates, increasing the risk of long-term health complications.[3] The issue is most prominent at the highest levels of specialised care, where capacity constraints are largely driven by severe shortages in nursing staff.[4] Nurses working at neonatal intensive care units (NICUs) are highly specialised, facing additional emotional and psychological burdens due to the unique patient population and the involvement of families leading to challenges in nurse retention and persistent vacancies.[5 6] Staffing shortages often lead to the closure of operational beds, resulting in antenatal maternal or postnatal neonatal transfers to other hospitals, sometimes even across national borders.[4] These transfers, which are increasingly reported in both national and international contexts, carry significant medical risks, induce stress for families and escalate healthcare costs.[3 7] Therefore, optimising neonatal care capacity—the availability of staffed and equipped operational beds to meet patient needs without undue delays or transfers—within existing staffing limitations is essential to maintaining high-quality care. It requires a regional or systemic approach to capacity allocation, rather than a focus on individual hospitals.

While most clinical and technical innovations in neonatal care primarily aim to improve quality of care, their impact on the hospital's resources and capacity, such as a decrease in length of stay (LoS) or reduction of interhospital transfers, is often a secondary consideration.[8] Although recent years have seen growing attention to the capacity impact of interventions, many studies still narrow their scope to selected aspects of capacity, typically from the patient perspective.[9] This narrow focus often overlooks the broader implications for neonatal care capacity, particularly at a regional level.[10] This is especially relevant given that neonatal care delivery is structured across multiple levels of care in different hospitals, typically centred around one highly specialised, tertiary-level, NICU.[11] This organisation of care needs to be considered to fully understand and effectively manage neonatal care capacity in regional neonatal care systems.

Modelling and simulation have been demonstrated to be appropriate approaches to address complex questions related to capacity, costs, feasibility and ethical constraints.[12] They are particularly useful for translating results of clinical trials or implementation studies into broader settings, for example, regional or national effects.[13] Simulation models offer insights into potential, and sometimes unexpected, side effects of interventions at a regional level, by enabling the simulation of patient transfer patterns between hospitals (ie, movements of neonates between facilities of different care levels based on medical needs and bed availability), including waiting times for available beds and changing allocation guidelines, and the effect of trends in time, such as increasing birth rates or changing operational hospital bed availability. A simulation model is particularly needed in this context because real-world testing of capacity interventions is often infeasible due to ethical, logistical and cost constraints. Furthermore, simulation models provide the opportunity to evaluate potential impact of an intervention, before conducting expensive and time-consuming trials. Moreover, commonly used capacity outcomes at the institutional level can be supplemented by regional measures, such as bed occupancy and interhospital transfers. Given the current neonatal care capacity challenges, simulation modelling is a powerful instrument complementary to traditional clinical trials, especially in studies that aim to address wider capacity and resourcing issues.

Despite the potential of simulation models to efficiently provide valuable insights into healthcare capacity, their application in neonatal care in previous work remains solely focused on single hospitals or wards,[14 15] or does not include intervention impact estimations.[16] Consequently, this study takes a foundational step as a proof of concept, aiming to demonstrate the feasibility of using simulation to assess regional capacity challenges in neonatal care. We developed a simulation model for neonatal care in the Southwest region of the Netherlands by simulating hypothetical scenarios based on real-world data, enabling evaluation of both the current capacity landscape and the expected capacity impact of targeted clinical interventions. This model was used to evaluate the current state of neonatal capacity and to assess the potential impact of several clinical interventions on regional capacity.

METHODS

We used a simulation model to evaluate capacity outcomes for neonatal care wards in a regional setting. The model development is based on perinatal birth registry data and supported by interviews and surveys with practitioners and hospitals.[17] The simulation method is reported in this section following the STRESS-DES guidelines, advising on standardised reporting of model purpose, structure, input data and experimental setup.[18] Following these, we described the context and setting of the model and the model requirements, including outcome measures. Next, the simulation model is explained in detail. Eventually, we present verification and validation, a status quo assessment and design of the experiments to evaluate interventions. Detailed information on the modelling process is presented in online supplemental file A.

Context and setting

The model focused on the Southwest of the Netherlands; the tertiary-level Erasmus MC-Sophia Children's Hospital together with 10 affiliated hospitals in the region (figure 1). In the Netherlands, neonatal care is categorised into three escalating levels of specialisation and intensity: medium-care neonatal (MCN) wards, high-care neonatal (HCN) wards and tertiary-level NICUs.[19] Tertiary-level NICUs, comparable to the American Academy of Paediatrics defined level III or IV NICUs,[11] manage the most critical cases, often involving newborns who are extremely premature or require assistance with vital functions like invasive mechanical ventilation and cardiovascular support for other indications. HCN wards typically cater to infants with a gestational age ≥32 weeks and weight ≥1250 g, or with a gestational age ≥30 weeks and weight ≥1000 g after an initial stay at a NICU. Patients who, although stable, still need significant medical attention,

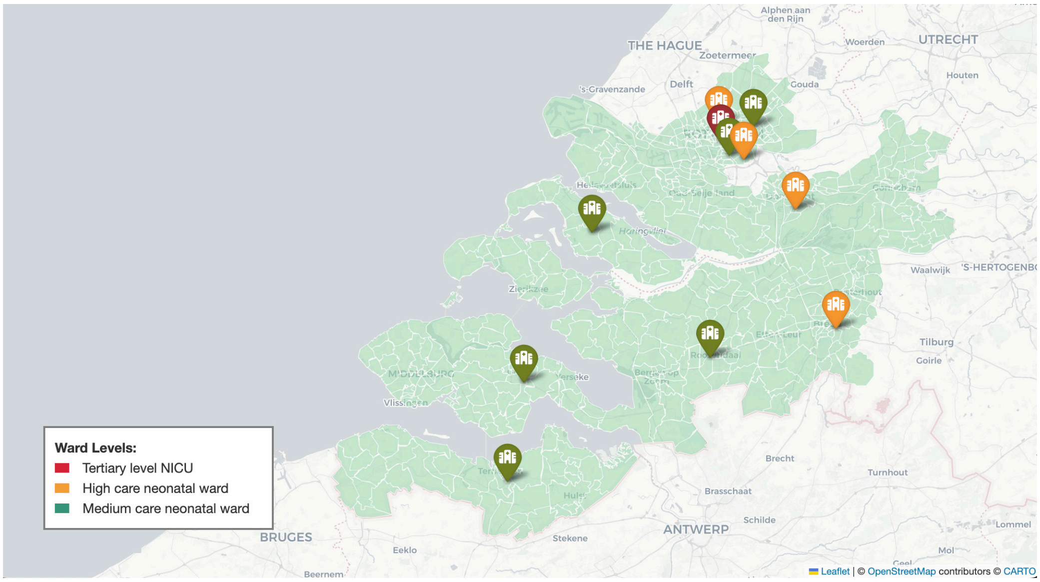

Figure 1 Overview map of the Netherlands outhwest region displaying hospitals with their respective ward level. NICU, neonatal intensive care unit.

such as non-invasive respiratory support or continuous monitoring. MCN wards handle cases that are less severe; these infants may need short-term non-invasive respiratory support and help with feeding or medications postbirth. Detailed information on the levels of neonatal care can be found in online supplemental file B.

The distribution of neonatal care wards across different hospitals, each offering varying levels of care, necessitates patient transfers to ensure that newborns receive treatment appropriate to their medical needs. These transfers include acute transfers to higher levels of care and back transfers to lower-level wards closer to home, once stabilised.

Model requirements

Conceptualisation

The conceptual model represents patient flow and interhospital transfers for neonatal admissions within the region consisting of 11 hospitals. The structure was developed and reviewed with neonatal medical experts in the region to ensure clinical realism. Our initial conceptualisation of the eventual simulation model is presented in figure 2.

Patients enter the model with baseline characteristics described in the *Model inputs* section and are categorised as inside region or outside region based on the maternal residential ZIP code. Ward level requirements and LoS are determined from clinical characteristics, including gestational age, birth weight and required treatments. Inside-region patients are assigned to the closest hospital of respective ward level using a subregion mapping, first within the home subregion and then sequentially across adjacent subregions until an available operational bed is found. If no bed is available within the region, transfer to an outside region hospital occurs. Outside-region, patients who are requesting admission in the region are assigned to the next available operational bed at the respective ward level.

After each admission, the model evaluates whether an additional stay is required. This assessment depends on the characteristics of the previous stay (eg, NICU patients with gestational age below 32 weeks require a subsequent post-IC stay) and on empirical probability distributions per ward level. If an inside region patient is first admitted outside the region and requires another stay, the region retains responsibility and attempts to arrange the next admission within the region. If an outside region patient is first admitted inside the region and requires another stay, the patient is discharged from the regional model and returned to an outside region hospital. A patient exits the simulation once no further stays are required.

Model inputs

Model input parameters were based on a comprehensive characterisation of the regional neonatal population and hospital capacity, using the Dutch national perinatal registry (2016–2021) and hospital surveys. Daily arrival rates and the distribution of maternal residential ZIP codes were derived from 2016 to 2017 data, which also underpin the classification of patients as inside region or outside region. Gestational age at birth was sampled from empirical distributions fitted to the 2016 to 2017 data. Birth weight was estimated by a regression model with gestational age as the predictor, fitted on 2016 to 2021 data to improve robustness. Clinical interventions such as continuous positive airway pressure (CPAP) and phototherapy were assigned using empirical probabilities conditional on gestational age and ward level. Expected LoS was predicted with regression models fitted on 2016 to 2021 data and stratified by ward level. Probabilities that govern additional stays and transitions between ward levels were estimated from the same empirical sources and are

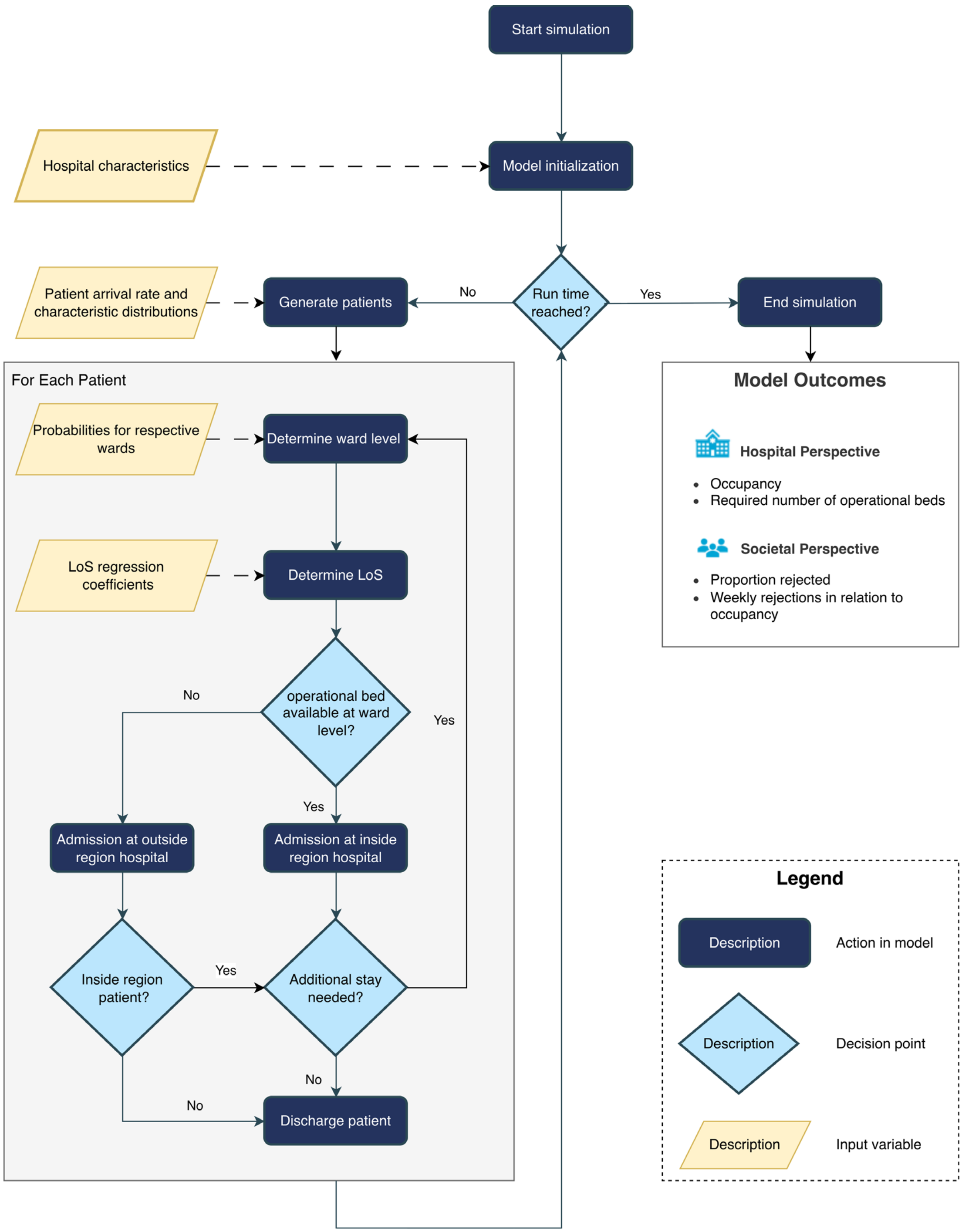

Figure 2 Model conceptualisation displaying the decision pathway in a patient's journey. LoS, length of stay.

applied conditional on the previous ward level. Hospital counts by ward level and operational bed numbers were obtained from surveys across the hospitals. This approach ensured realistic arrival patterns and plausible patient profiles for simulation.

Model outcome measures

Four model outcome measures were defined to assess the current regional neonatal capacity and the impact of interventions. The outcome measures were grouped based on two perspectives: a hospital management perspective and a wider societal perspective on capacity shortages.

From a hospital management perspective, we report (1) the occupancy and (2) the required number of operational beds needed to care for all inside-region patients under the assumption of a target occupancy of 85%. The required number of beds was calculated by dividing the total simulated bed-days used per ward level by 365 days and adjusting for the 85% target occupancy. This provides a benchmark indicating how many operational beds would be needed to meet current demand while maintaining sufficient flexibility for acute admissions. Both the occupancy and the number of required operational beds were aggregated per ward level.

For the societal perspective, we assessed (3) the proportion rejected, defined as the percentage of inside-region neonates in need of a transfer to an outside-region hospital due to no available bed at the preferred ward level as part of the total inside region patients. As an additional outcome measure, we present (4) the number of weekly rejections in relation to the occupancy aggregated per ward level.

Model assumptions

Considering the project's scope, we made several assumptions in the modelling process. These assumptions were based on three key informant interviews with neonatologists at HCN and tertiary-level NICU (topic guide in online supplemental file C), and an unpublished survey across all neonatal wards in the region, previously performed by JHLW (results in online supplemental file B):

- The outside region has unlimited bed capacity and can always accept a patient, acknowledging that the healthcare system will always find a way to provide care even if this requires transport to another region or even country.
- Hospitals of the same ward level can provide the same level of care, resulting in no difference in LoS for a hospital, as each hospital has at least one neonatologist that is required to have regular training at the NICU and adhere to the same guidelines.[20]
- The daily patient arrival rate follows a uniform distribution across the simulation period as no statistically significant differences in the number of arrivals across seasons were found in the available data.
- Additional stays, that is, two or more hospital admissions, are always first attempted in the closest appropriate hospital to the home location to minimise additional stress and efforts for parents.
- The data set is representative of future patient populations and range of data values (eg, birth weight) will not change significantly in the next years.
- For back transfers from the tertiary-level NICU to HCN or MCN, the model included a waiting time of 2 days maximum for an available bed before outside region transfer was initiated to enhance clinical representativeness.

Model simplifications

In addition, we incorporated the following simplifications to ensure a practical trade-off between model complexity and accuracy.

- The model does not allow for overflow beds, and each additional patient is transferred if the hospital has no availability.
- The bed numbers, as collected through a survey across all hospitals, were assumed to be constant for the simulation period of 1 year, based on input from one interview, previously performed regional capacity analysis[4] and statistical analysis of the maximum number of daily admissions per hospital.

Simulation model

Selected approach: discrete event simulation

Based on the conceptualisation and the desired outcomes, we used discrete event simulation (DES) due to its ability to define patient pathways and its efficient runtime. DES has been widely used in healthcare and other operations research. Common applications include patient flow management, hospital bed management and scheduling and resource allocation.[12] In a DES model, patients can undergo a series of queues to receive services. Furthermore, individual stops can be based on random sampling (eg, chance of additional stay) or predefined logic (eg, all patients below 32+0 weeks are admitted at the NICU first). Hence, the approach is suitable in modelling the neonatal care system.

Simulation model development

The model was developed in the open-source programming language Python using the DES simulation package salabim.[21] Each simulation resulted in an output data file (of comma-separated values) with all admissions and occupancy that was further analysed (using Jupyter notebooks) to obtain the model outcome measures. The model is open source under the MIT licence. Additional details can be found in the GitHub repository (https://github.com/alex-dietz/Discrete-Event-Simulation-for-Neonatal-Care-System).

Data collection and preparation

Model development and validation was based on different data sources. First, we used data from the Dutch perinatal birth registry Perined (www.perined.nl) between 2016 and 2021. The data set included neonatal admissions from the 11 hospitals in the region, and admissions of patients with a maternal residential address within the region who were admitted to a hospital outside the region. With these inclusion criteria, the data set included admissions from both inside-region and outside-region patients and of patients who passed away. Data were deidentified before access was granted to the researchers. The data included (1) patient characteristics—like gestational age and birth weight, (2) information on the stay—like LoS and hospital ID and (3) any performed treatments—such as CPAP or phototherapy (online supplemental file D provides the complete list). The data were explored and cleaned to ensure quality. Accuracy was addressed through plausibility checks of all key values in consultation with medical experts. Completeness was confirmed by ensuring that all relevant patient, admission and treatment information was available. Consistency checks verified the logical order of events, such as admission and discharge dates. Outliers were reviewed with experts and corrected where needed, for example in cases of typos or implausible weights. For the simulation model, patient characteristics were predicted based on medical characteristics of all patients included. Probabilities of patient pathways were estimated based on the admission data between 1 January 2016 and 15 October 2017 as a change in reporting guidelines led to reporting inconsistencies for individual HCN and MCN after this period.

Second, the data on hospital bed capacity in 2021/2022 were collected via retrospective questionnaires.[4] Third, we collected additional more recent data for validation from January 2023 to July 2024 through a survey of the hospitals in the region. The link to the survey can be found in online supplemental file E. Validation data were available for validation for six out of 11 hospitals.

Verification and validation

Model verification and validation were performed to ensure that the model functions properly and is able to represent the real-world system. For the verification, we tested whether each part of the model functioned as intended, including the correct creation of patients with respective characteristics and the accurate simulation of their treatments and care pathways. In addition, we verified the model functions for admission, LoS calculation and additional stays. For the validation, we first performed a historical data validation by comparing arrival processes, LoS, pathways and model outcomes to the initial Perined data set between 1 January 2016 and 15 October 2017. Furthermore, model outcomes were validated through face validation via key informant interviews (n=3). Finally, we performed a time validation by confirming operational bed numbers and LoS to data from 2023 and 2024 for available hospitals (online supplemental file E). No structural changes were made after validation to prevent over-calibration of the model, and therefore only parameters were adjusted to better align simulated outputs with observed data and expert expectations.

Status quo assessment

To evaluate capacity outcomes in the current situation under capacity strain, the operational bed numbers of the hospitals in May 2023 were used.[4] For generating model outcomes, the model was run for 365 days with a daily time step as the goal was to provide a direct impact assessment and there is no evidence of demographic changes that would make a multiple-year analysis necessary.[4] Warm-up time of 70 days until steady state was determined once the data showed no substantial variation across consecutive time intervals through visual inspection.[22] For each simulation run, patient characteristics, pathways and LoS were randomly sampled from the fitted empirical distributions and regression models, using a different random seed per run to ensure independent stochastic realisations. To ensure robustness, 100 iterations were simulated to achieve statistically reliable and consistent outcomes.[23] CIs for all model outcomes were calculated using the normal approximation based on the SE of the mean, assuming an approximately normal distribution across simulation runs. Paired two-sided t-tests were performed to assess the statistical significance of differences between the baseline and intervention scenarios, with p-values reported accordingly. A threshold of 0.05 was deemed to be statistically significant.

Intervention impact assessment

We implemented three currently relevant clinical interventions in the simulation model to demonstrate the potential of the simulation model in assessing the regional capacity impact of clinical interventions. The three interventions were selected based on their current clinical relevance and alignment with ongoing or recently piloted initiatives in the investigated neonatal care system. They were chosen because they directly impact patient flow and LoS—key determinants of capacity strain—and because sufficient clinical data and expert input were available to enable accurate implementation in the simulation model. The simulation details are described in online supplemental file A.

- *Intervention 1: phototherapy at home*
  Phototherapy for low-risk neonatal hyperbilirubinaemia is currently predominantly provided in hospitals in the Netherlands, while research has shown that it can also be safely applied at home.[24] Thus, current trials test the potential of discharging patients without any other condition than hyperbilirubinaemia to provide phototherapy at home, reducing the LoS to only 1 day for these patients.[24,25]
- *Intervention 2: oral antibiotics for EONS*
  Switching from intravenous to oral antibiotics for culture-negative early-onset neonatal infection represents a safe and efficacious intervention.[26] Implementation studies showed a decrease in average LoS from 7 days to 3.5 days when switching to oral treatment for patients with culture-negative early-onset neonatal infection.[26,27]
- *Intervention 3: changing tertiary-level NICU guidelines*
  While Dutch guidelines advise neonates to be born in a tertiary-level NICU centre before 32 weeks of gestation, the majority of those close to the threshold are not in need of tertiary-level NICU care. Internal data of the Erasmus MC tertiary-level NICU showed that approximately 70% of neonates born between 30 and 32 weeks of gestation with a birth weight above 1000 g did not require tertiary-level NICU care. Therefore, as a simulated intervention, guidelines were changed from 32 to 30 weeks of gestation, assuming 30% of those needed transfers from HCN to the NICU.

Patient and public involvement statement

Patients and parents were not involved in the design, or conduct, or reporting or dissemination plans of our research. Obstetric and neonatal representatives from the regional acute care coordination organisation (ROAZ-Zuidwest Nederland) were involved in the design of the study.

Table 1 Descriptive characteristics of all included admissions

Ward level	NICU		HCN		MCN	
GA group	≤32	>32	≤32	>32	≤32	>32
Number of patients	1936	2606	936	21 487	157	21 058
LoS*	12 (5–29)	3 (2–6)	42 (27–53)	2 (1–4)	23 (1–34)	2 (1–3)
GA at birth*	29+3 (27+2–30+5)	37+2 (34+5–39+2)	29+5 (28+1–30+6)	39+0 (37+3–40+2)	30+4 (29+4–31+3)	39+2 (38+0–40+3)
Birth weight*	1220 (920–1510)	2865 (2185–3430)	1274 (1009–1576)	3285 (2829–3688)	1520 (1253–1740)	3355 (2930–3740)
PMA at admission to specific ward level*	29+5 (27+4–31+0)	37+3 (34+6–39+3)	31+4 (30+4–32+4)	39+0 (37+4–40+2)	31+3 (30+1–32+0)	39+2 (38+0–40+3)
Mortality	168 (8.7%)	105 (4.0%)	2 (0.2%)	4 (0.0%)	1 (0.6%)	4 (0.0%)

*Data presented as median (IQR).
GA, gestational age; HCN, high-care neonatal unit; LoS, length of stay; MCN, medium-care neonatal unit; NICU, neonatal intensive care unit; PMA, postmenstrual age.

RESULTS

The results are structured as follows: first, a detailed characterisation of the study population is presented, highlighting the diversity of patients and variations across care levels. Next, the capacity outcomes of the simulation model were analysed, focusing on the current situation to confirm the extent of observed capacity shortages, that is, the status quo assessment. Finally, the impact of the selected interventions on the model's outcomes is presented.

Characterising the study population

The data set used for model development included 48 180 admissions for 44 461 neonates born between 2016 and 2021, with a median gestational age of 39 weeks and 0 day (IQR: 37+1–40+2) and birth weight of 3130 g (IQR: 2568–3674). The average LoS was 5.2 days, with a median of 2 days (IQR: 1–4). Table 1 shows characteristics of neonatal admissions presented per ward level and gestational age group.

The majority of patients (96.7%) experience a single stay, with the largest proportions in HCN (53.6%) and MCN (38.6%) (table 2). Pathways including an interhospital transfer, such as NICU to HCN (1.9%) and NICU to MCN (0.2%), show substantially longer total LoS. These pathways primarily consist of very preterm newborns. The median combined hospital LoS for patients staying first at the NICU and then at the HCN was 50 days (IQR: 26–69 days).

Status quo assessment

The simulation model of neonatal care across 11 hospitals reveals significant capacity challenges, particularly in HCN and NICU (top row of table 3). Simulated mean occupancy was highest in HCN at 98.1% (95% CI 98.1 to 98.1) and NICU at 91.7% (95% CI 91.6 to 91.8), indicating

Table 2 Most common neonatal care pathways of inside region hospital admissions between 1 January 2016 and 1 October 2017

Pathway	Number of patients	Total length of stay (days)	Gestational age at birth (week+day)
Single stay	15 921 (96.7%)	2 (1–3)	39+0 (37+5–40+2)
NICU	737 (4.5%)	4 (2–11)	35+0 (29+1–38+2)
HCN	8831 (53.6%)	2 (1–3)	39+0 (37+6–40+2)
MCN	6353 (38.6%)	2 (1–3)	39+1 (38+0–40+3)
NICU-HCN	309 (1.9%)	50 (26–69)	30+6 (29+1–32+5)
MCN-NICU	70 (0.4%)	7 (5–9)	38+2 (34+5–40+1)
HCN-NICU-HCN	52 (0.3%)	24 (12–37)	35+0 (33+0–38+2)
HCN-NICU	46 (0.3%)	15 (6–34)	38+0 (36+0–39+5)
NICU-MCN	29 (0.2%)	15 (6–34)	33+6 (31+6–38+3)

Data are presented as median (IQR).
HCN, high-care neonatal unit; MCN, medium-care neonatal unit; NICU, neonatal intensive care unit.

Table 3 Results of simulation experiments given current operational bed numbers and the three main performance indicators

	Occupancy			Required beds†			Proportion rejected		
	MCN	HCN	NICU	MCN	HCN	NICU	MCN	HCN	NICU
Current situation	64.5 (64.1–64.8)	98.1 (98.0–98.2)	91.7 (91.4–92.0)	39.4 (39.2–39.7)	88.4 (87.9–89.0)	31.7 (31.4–32.0)	0.05 (0.03–0.07)	24.5 (24.0–25.0)	22.4 (21.8–22.9)
Phototherapy at home	63.4** (63.0–63.8)	98.0* (97.9–98.0)	91.6 (91.3–91.9)	38.8** (38.6–39.0)	87.6* (87.1–88.1)	31.6 (31.2–31.9)	0.03 (0.02–0.04)	23.8* (23.4–24.2)	22.1 (21.5–22.7)
Oral antibiotic switch	60.4** (60.0–60.8)	97.9** (97.8–97.9)	91.5 (91.2–91.8)	37.1** (36.8–37.3)	86.9** (86.4–87.4)	31.3* (31.0–31.6)	0.01** (0.0–0.02)	23.2** (22.7–23.7)	21.6* (21.0–22.2)
Change NICU guidelines	63.0* (62.6–63.3)	99.1** (99.1–99.2)	85.1** (84.6–85.6)	38.6** (38.3–38.8)	103.1** (102.5–103.8)	25.2** (24.9–25.5)	0.02* (0.01–0.03)	34.3** (33.8–34.8)	11.1** (10.4–11.7)
Combined	58.8** (58.4–59.2)	99.0** (98.9–99.0)	84.1** (83.5–84.6)	36.1** (35.9–36.3)	100.5** (99.9–101.1)	24.7** (24.4–25.0)	0.00** (0.00–0.00)	32.7** (32.2–33.1)	10.5** (10.0–11.1)

Data presented as mean (95% CI). The weekly rejections in relation to occupancy can be found in online supplemental file F.
*P value below 0.05 for t-test comparing to current situation.
**P value below 0.001 for t-test comparing to current situation.
†Current actual beds: NICU 23, HCN: 58, MCN: 54.
HCN, high-care neonatal unit; MCN, medium-care neonatal unit; NICU, neonatal intensive care unit.

substantial capacity pressure on these units. In contrast, MCNs operated at a much lower occupancy (63.9%), suggesting potential excess capacity. The required total number of beds to achieve an optimal 85% occupancy was significant, especially for HCN (88.4 beds, in respect to the current 58 beds) and NICU (31.7 beds, in respect to the current 23 beds), highlighting a gap between current capacity and ideal levels. The proportion rejected, representing the percentage of neonates transferred to an outside region hospital due to capacity shortages, was high, particularly in HCN (24.5%) and NICU (22.4%). The number of weekly rejections exponentially increased with increasing occupancy starting from 85% at the HCN, 87% at NICU and 92% at MCN (figure 3). The observed outcomes align with historical and current actual values as confirmed in our historical data validation.

The interaction between these outcomes underscored the strain on the system. The simulation showed that the occupancy at HCN and NICU is positively correlated with the proportion rejected, demonstrating that wards nearing full capacity trigger more patient transfers. Comparatively, the relatively low occupancy in MCN, combined with its proportion rejected of 0.05%, suggested that capacity shortages were not a phenomenon at those hospitals and, hence, mostly impacting specific patient groups.

Intervention impact assessment

The simulation results presented in table 3 highlight several key performance changes across the three different interventions (details can be found in online supplemental file F). The implementation of phototherapy at home showed a minor but statistically significant reduction in the MCN occupancy, from 64.5% to 63.4% (p<0.001), while NICU occupancy remained unchanged. This intervention also marginally decreased the proportion rejected for HCN, from 24.5% to 23.8% (p<0.05). When implementing oral antibiotic switch for early onset sepsis, the occupancy at MCN significantly dropped from 64.5% to 60.4% (p<0.001). There was no significant impact observed on the proportion rejected. The change in tertiary-level NICU guidelines highlights a trade-off between use of HCN and NICU beds. The number of required beds at HCN level increased significantly to 103.1 with a significant reduction to 25.2 for NICU (p<0.001). Notably, combining all interventions demonstrated the most substantial decrease in occupancy for MC and NICU, with MC occupancy dropping to 58.8% and NICU to 84.1% (p<0.001). However, there is a trade-off with the burden on HCN leading to a proportion rejected of 32.7%, while it decreased to 10.5% for NICU (p<0.001). A similar trade-off between NICU and HCN can be observed for the number of required beds.

DISCUSSION

We present a DES model based on historical data from 48 180 neonatal admissions over a period of 5 years (2016–2021) in 11 hospitals in the Southwest of the Netherlands.

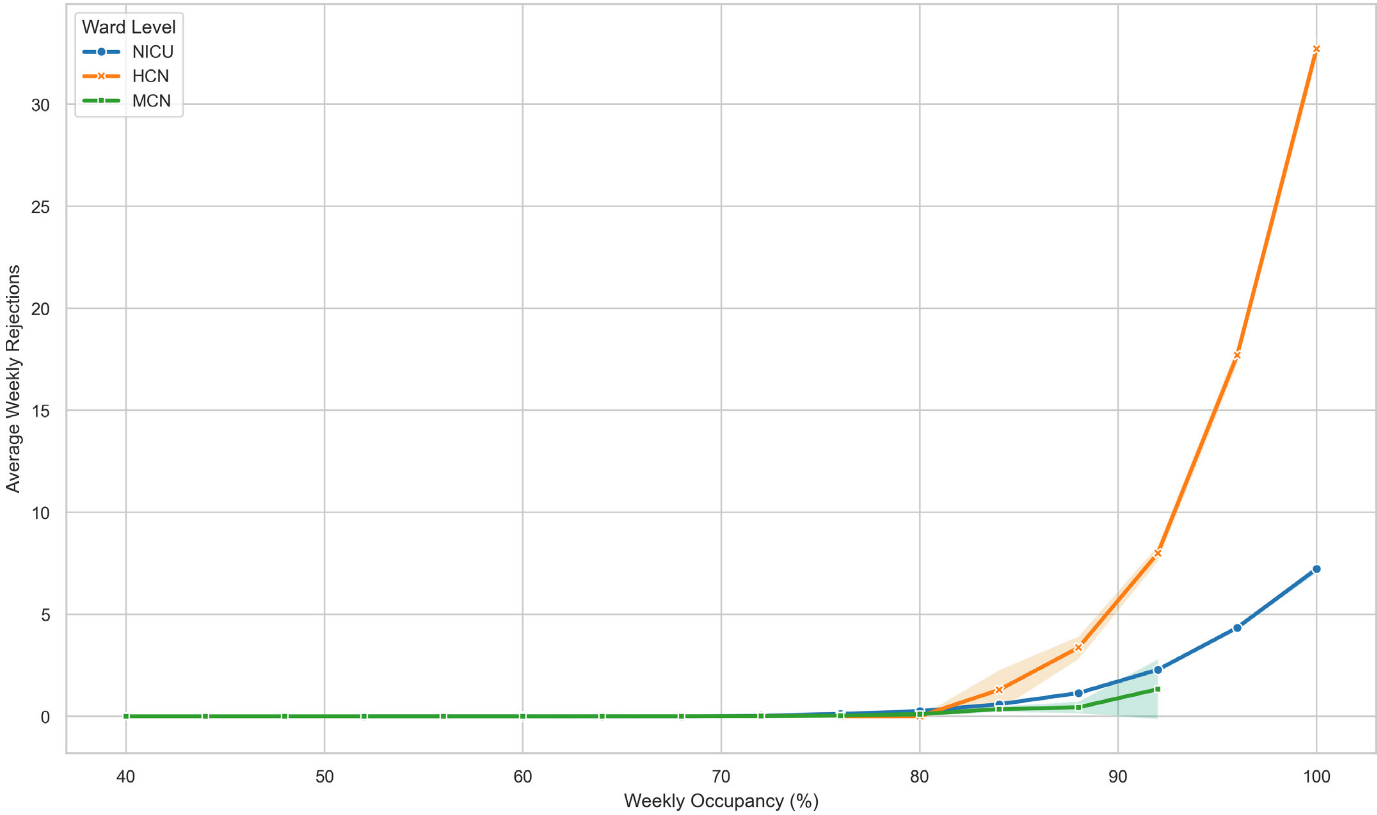

Figure 3 Average weekly rejections per weekly occupancy rate for the different ward levels. HCN, high-care neonatal unit; MCN, medium-care neonatal unit; NICU, neonatal intensive care unit.

The model provides insights into predefined capacity outcomes; namely (1) occupancy, (2) required beds to provide care to all patients in the region and remain flexible for acute admissions (advised occupancy of 85%) and (3) outside region transfers caused by rejections of patients. In the current situation ('status quo' assessment) with nursing staffing shortages leading to closure of beds, the occupancy at the tertiary-level NICU and HCN was extremely high (respectively 91.7% (95% CI 91.4 to 92.0) and 98.1% (95% CI 98.0 to 98.2)) and the number of required beds largely exceeded the available operational beds in the region. These capacity issues resulted in a proportion rejected of 24.5% and 22.4% for inside region tertiary-level NICU and high care patients to a hospital outside of the region. An exponential correlation was observed between occupancy and rejections after the former exceeds 85%. This trend underlines the fragility of the current capacity system under heavy demand.

Following the 'status quo' assessment, three clinical interventions were simulated to assess their impact on neonatal capacity; namely (1) home-based phototherapy for neonatal hyperbilirubinaemia, (2) oral antibiotic switch for culture-negative early-onset sepsis and (3) a change in NICU admission guidelines. The interventions influenced the LoS or pathways of patients and demonstrated significant, but marginally clinically relevant impact on occupancy and required bed indicators. Notably, the change in NICU admission guidelines showed a trade-off across all indicators between HCN and NICU. Overall, a combined intervention strategy of all individually tested interventions could ease the capacity strains on the NICU but would result in an increased burden on the HCN.

Interpretation of findings

By conceptualising the key elements of neonatal care in the region, and analysing an extensive data set, we highlighted the heterogeneity and complexity of the neonatal population in the region. In particular, the differently specialised ward levels, including back transfers once a patient is stabilised, were shown to be essential in optimising capacity and ensuring that each patient receives the necessary care. The results of the simulation confirmed that there are severe ongoing capacity strains in neonatal care for this region in the Netherlands, probably linked to nursing staffing shortages.[4] Furthermore, our simulation showed that future interventions or guideline changes could significantly influence capacity, an outcome not often considered in the design of intervention studies. As such, our study demonstrates the importance of including capacity evaluations in neonatal research; not only when investigating interventions that are expected to reduce capacity impact but also when a potential increase in LoS or admissions is hypothesised. An important example is the recent discussion on offering active care to extreme preterms from 23 weeks of gestation, instead of 24 weeks, in the Netherlands.[28 29] Having available hospital capacity to provide care for these neonates is an important condition, although ideally not being one of the arguments in this discussion. In addition, the results highlight that neonatal capacity strain is a system-wide challenge, where changes at one ward level can create cascading effects across the regional neonatal care system, reinforcing the need for integrated, whole-system planning.

Finally, we were able to simulate the individual and combined effects of each intervention. The expected impact of a switch to oral antibiotic treatment following culture-negative early onset sepsis showed a greater capacity impact compared with phototherapy at home. Nevertheless, both had a marginal impact on NICU capacity. Changing NICU admission guidelines could therefore be a priority when aiming to optimise NICU capacity but is only feasible when combining with other interventions or trends that relieve pressure of the HCNs. The relatively limited impact of these care innovations on reducing capacity strain emphasises the continued need to develop effective preventive approaches to common indications for neonatal admission, such as preterm birth and low birth weight. Optimising patient flow to MCNs might also be a solution given the marginal capacity strain observed at that ward level. Thus, these findings have operational, clinical and policy relevance by showing that the model can identify capacity trade-offs, guide redistribution strategies between ward levels and assess the capacity impact of proposed interventions before they are implemented.

Strengths and limitations

This study effectively showcases the practical application of simulation models in neonatal care, demonstrating their potential to bridge the gap between academic research and decision-making. The model is open source, making it transparent, accessible and adaptable to other regionalised healthcare settings, multiple regions and to the addition of new interventions by using the existing ones as templates. Furthermore, we acknowledge that the scope of this study was to focus on capacity, which we consider as increasingly relevant for neonatal care planning given current resource constraints, especially in light of ongoing clinical research on the safety and efficacy of the interventions studied. While this focus is important, there is potential for future work in exploring effects on capacity as well as more studied indicators such as safety and efficacy. For the phototherapy at home and oral antibiotics interventions, parent and patient organisation perspectives have already been incorporated into previous research. For the change in admission guidelines, parental views were not collected in this study, although similar practices are already implemented in other European hospitals for 30–31 week neonates in level II and high care units.

The model's scope is currently limited to a single region in the Netherlands, which may affect the generalisability of the findings. Other regions in the Netherlands have a comparable structure of affiliated regional hospitals, suggesting some transferability of our findings, although model parameters would need to be tuned to account for regional differences in patient flows, resources or care practices. The results require further validation across different regions to confirm their applicability in varied geographical and healthcare contexts. Additionally, the model's results might not be directly transferable to neonatal care systems that do not operate within a regionalised network with a similar organisation.

Moreover, some results may be sensitive to choices regarding model assumptions and simplifications. First, the simulation model focused on neonatal wards and currently does not include interacting hospital settings, such as paediatric and obstetric wards. Second, the fact that the model did not allow for overflow beds and the assumption that outside region hospitals always had capacity available could result in an overestimation of the rejection transfers. In reality, neonatal care systems in the Netherlands and surrounding Western European countries are highly developed and coordinated, ensuring that no critically ill neonate remains untreated. Transfers across regions or temporary operation above nominal capacity are routinely used to manage surges. While hospitals may differ in specific capabilities, such as extracorporeal membrane oxygenation or paediatric surgery, these cases are handled through established referral pathways and do not affect the core capacity dynamics we model. The assumption that the operational bed numbers were stable over a year period could underestimate the capacity strain, since seasonal closure of extra beds, for example, in summer holiday period, was not considered. Furthermore, the assumption of constant operational bed numbers throughout the simulation period and uniform care quality across hospitals of the same ward level may not fully reflect real-world variability and could influence the accuracy of model outcomes. Finally, the assumption that our patient data are representative of future neonatal care patterns could influence the generalisability. To minimise this limitation, we performed a time validation with up-to-date admission data. Unfortunately, this data originated from hospitals' own administration instead of being consistent in format with the Perined registration of the original data set. This limitation was caused by inconsistencies in reporting, due to the reporting being obligatory only for NICUs. These factors could have influenced the accuracy of the validation results and may lead to either underestimation or overestimation of model performance for specific hospitals or care levels.

Future research

For future research, we propose to extend the current model to include obstetric care pathways, especially since capacity issues in obstetric care are increasing in the highlighted Dutch region and both care specialties greatly influence each other. Furthermore, an important next step is to adapt and extend the model to other regions in the Netherlands to enable assessment of capacity impacts at a national level. Such scaling would support regional and national policymakers in planning resources, coordinating capacity and evaluating system-wide effects of proposed interventions. Incorporating cost analysis into the model could further strengthen its practical utility by enabling cost–benefit evaluations alongside capacity outcomes. Moreover, we recommend simulating interventions that focus on other mechanisms than LoS reduction and admission rates to provide additional 'blueprints' for intervention implementation. One of these additional interventions could investigate the impact of prevention policies, such as smoking cessation support to future parents.[30] Also, we urge the medical community to acknowledge the impact on bed capacity as a health system performance indicator and include it in their assessments of clinical interventions. In this context, research should also focus on interventions tackling capacity strains while acting within staffing limitations. Finally, creating a graphical user interface for the model, such as a web-based dashboard, could be a practical usability improvement of the simulation model. That dashboard could be used for easy adjusting of input parameters and to visualise capacity outcomes of different interventions. With that, simulation models can serve as effective communication tools and help decision-makers prioritise different interventions.[31]

CONCLUSION

Operational bed capacity strains continue to be one of the major burdens in multiple healthcare systems and are especially relevant in regionally organised neonatal care, hence, asking for novel approaches to overcome these challenges. In this study, we showed how simulations can provide a meaningful approach for capacity impact assessments, especially as conducting longitudinal studies targeted at capacity impacts is challenging in real-world settings. Our DES model quantified the currently experienced capacity strains based on clinical data of over 48 000 neonatal admissions. The tested interventions showed some potential to reduce neonatal capacity strain, especially when they are combined. This proof-of-concept highlights how simulation models can provide easy-to-use and low-cost impact assessments and therefore open opportunities to assess the capacity situation in a wider context (eg, a region) instead of a single or few hospitals.

Acknowledgements This work is supported by Convergence | Healthy Start, a programme of the Convergence Alliance—Delft University of Technology, Erasmus University Rotterdam and Erasmus Medical Centre—to improve the future of new generations. Furthermore, the authors acknowledge with thanks the 11 hospitals in the Southwest region of the Netherlands for sharing their data for model development and validation.

Contributors JHLW was responsible for conceptualisation, methodology and interpreting of the results, together with AD and SH-K. AD was responsible for data preparation, data analysis and model development. YH was responsible for supervising model development. AD, JHLW, YH and SH-K performed model verification and first interpretation of the results. HRT, IKMR, JS, JVB and RFK provided clinical input to contribute to the design of the model, expert validation of the model and contributed to the interpretation of the results. AD and JHLW were responsible for writing the first version of the manuscript. JHLW, AD, YH, IKMR, JVB, JS, RFK, HRT and SH-K reviewed and critically revised the intellectual content of the manuscript. All authors read and approved the final version of the manuscript. SH-K is responsible for the overall content as guarantor.

Funding The authors have not declared a specific grant for this research from any funding agency in the public, commercial or not-for-profit sectors.

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Competing interests None declared.

Patient and public involvement Patients and/or the public were not involved in the design, or conduct, or reporting or dissemination plans of this research.

Patient consent for publication Not applicable.

Ethics approval This study involves human participants and ethical approval was provided by the Human Research Ethical Committee of Delft University of Technology (application number: 4299). Approval under the Dutch Medical Research Involving Human Subjects Acts was not required, since this study used registry data from the Dutch Perinatal Registry Perined. Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement All data relevant to the study are included in the article or uploaded as supplementary information. Both the full model and the analytic code are available via GitHub under the MIT licence (https://github.com/alex-dietz/Discrete-Event-Simulation-for-Neonatal-Care-System). The data set with patient characteristics is not available due to the detailed level of personal data (ZIP codes in combination with date of birth). Instead, a dummy data set is provided on GitHub to ensure functioning model. Anonymised data on hospital characteristics are available upon reasonable request from the authors.

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