Appendix 1 Two-stage semi-parametric modeling analysis

To further improve the robustness of study analysis, we also employ a robust two-stage semi-parametric modeling approach. This methodology enhances the conventional data envelopment analysis (DEA) by integrating a second stage of statistical inference through bootstrapping, allowing for a better understanding of efficiency determinants (62). This appendix details the process and rationale behind this approach, drawing on insights from our comprehensive dataset.

Stage one: *DEA efficiency scores*

The first stage of our analysis involved the computation of DEA efficiency scores. Utilizing the "rDEA" library in R, we adapted an output-oriented model with variable returns to scale, acknowledging the diverse operational scales of hospitals. The input and output measurements were the same as the ones in our main analysis in the manuscript. That is, inputs comprised three primary variables: case mix index, number of beds, and full-time equivalent total personnel as hospitals input, and the outputs included desirable metrics: total admissions and inpatient and outpatient surgical operations, alongside inverted metrics for undesirable outcomes: CLABSI rates, AMI mortality, and AMI readmission rates. To align with this two-stage semi-parametric modeling approach requirement, we included the following environmental variables hospital ownership, teaching affiliation, location rurality, and HHI. These variables encapsulate both operational and market conditions, offering a broader perspective on hospital efficiency.

Given the variability in operational environments and strategic positioning among hospitals, the DEA model was enhanced to reflect these factors. This approach underscores the complexity of healthcare service delivery, acknowledging that efficiency is influenced by a mosaic of internal and external factors.

Efficiency scores were derived, revealing a spectrum of performance across the evaluated hospitals. To illustrate, we plotted these scores, highlighting the distribution and identifying the threshold for the top 5% of efficient hospitals. This threshold was determined through a rigorous analysis of the distribution of DEA scores, identifying a cutoff that represents exemplary performance in the context of environmental constraints and opportunities.

Stage two: *bootstrapping for statistical inference*

Building on the foundation of DEA scores, the second stage introduced bootstrapping, as implemented through the "boot" library in R. This technique enabled us to account for the inherent bias and variability in DEA scores, facilitating robust regression analysis. By resampling with replacement, we constructed a distribution of efficiency scores. We followed the same steps used in the main section of DEA analysis in the manuscript.

Before conducting the regression analyses, we checked that all necessary linear regression assumptions had been met. After removing outliers using Cook's distance method, we determined that a log transformation of the dependent variable (efficiency scores) was more appropriate to meet the assumptions of linear regression. As a result of this transformation, the variance of our model was stabilized, and its interpretability was improved.

Compared to DEA results, the number of efficient hospitals decreased from 95 to 22. Furthermore, the efficiency advantage of the financial and clinical hybrid PHI type was diminished in the new model, partly because we set the threshold for the top 5% of efficient hospitals. However, the regression outcomes from this two-stage model align closely with our main analysis. For detailed information, refer to *Tables S1-S3* and *Figures S1-S2*.

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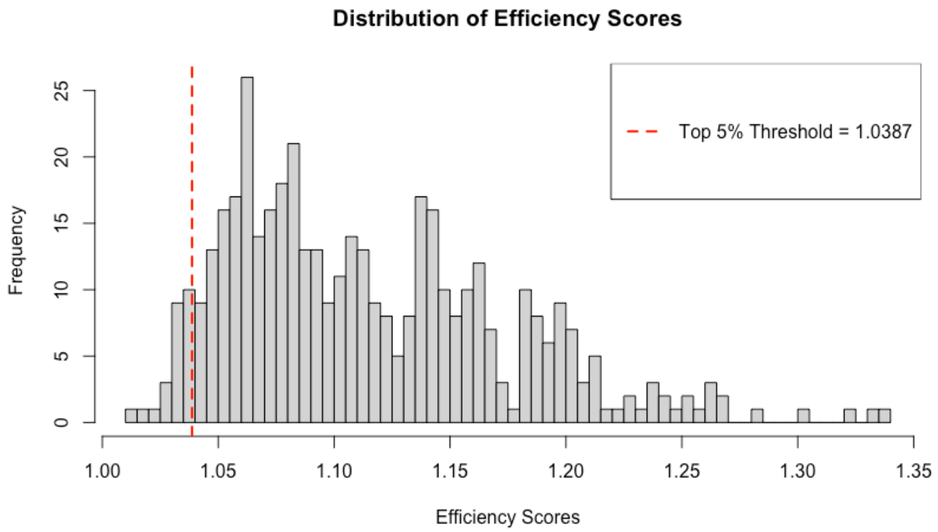

Figure S1 Distribution of efficiency score from DEA (with the two-stage modeling). DEA, data envelopment analysis.

Table S1 DEA results (with the two-stage modeling) (N=434)

Item	Efficient hospitals	Inefficient hospitals
Number	22	412
Percentage	5%	95%
Average DEA scores	1.031	1.119

DEA, data envelopment analysis.

Table S2 DEA results with PHI at both hospital and system level (with the two-stage modeling)

PHI type	Hospital-level PHI (N=321)		System-level PHI (N=326)	
	Efficient hospitals	Inefficient hospitals	Efficient hospitals	Inefficient hospitals
Financial PHI (Integrated Salary Model)	10 (5%)	175 (95%)	9 (5%)	168 (95%)
Financial and clinical hybrid PHI (Physician-Hospital Organization)				
Open Physician-Hospital Organization	3 (5%)	60 (95%)	4 (6%)	64 (94%)
Closed Physician-Hospital Organization	0	25 (100%)	2 (9%)	21 (91%)
Clinical PHI (Independent Practice Association)	1 (2%)	47 (98%)	1(2%)	57 (98%)

DEA, data envelopment analysis; PHI, physician-hospital integration; PHO, Physician-Hospital Organization.

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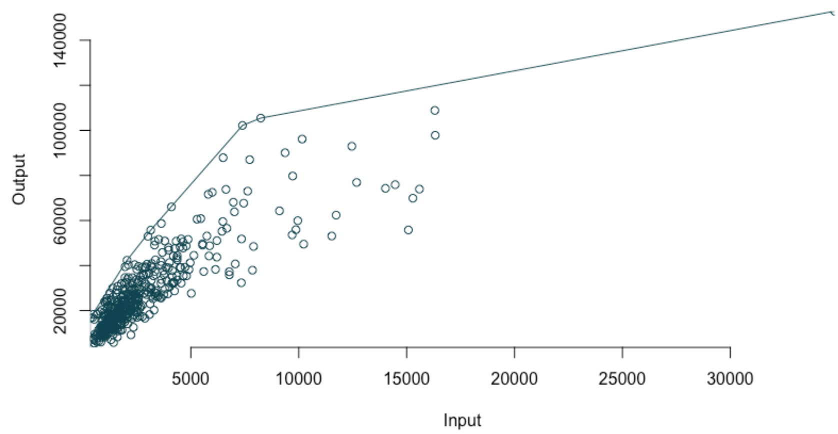

Figure S2 DEA efficiency plot (with two stage measures). DEA, data envelopment analysis.

Table S3 Regression results for DEA efficiency scores (with the two-stage modeling) (N=434)

Measures	Dependent variable (efficiency score), β (SE)	
	Hospital-level PHI	System-level PHI
PHI categorizations		
Financial PHI (Integrated Salary Model)	−0.002 (0.005)	0.001 (0.005)
Financial and clinical hybrid PHI (Physician-Hospital Organization)		
Open Physician-Hospital Organization	0.002 (0.006)	−0.014* (0.006)
Closed Physician-Hospital Organization	0.011 (0.009)	−0.015 (0.010)
Clinical PHI (Independent Practice Association)	−0.002 (0.006)	0.002 (0.006)
Organizational characteristics		
Hospital ownership (non-profit)	0.023** (0.008)	0.028*** (0.007)
Number of beds (hospital size)	0.000* (0.000)	0.000* (0.000)
Staffing/FTE	0.000 (0.000)	0.000 (0.000)
Teaching affiliation	−0.004 (0.005)	−0.005 (0.005)
Case mix index	0.042*** (0.010)	0.042*** (0.011)
Location rurality (metro)	0.023** (0.007)	0.024*** (0.007)
Market characteristic		
Herfindahl-Hirschman Index	0.000 (0.000)	0.000* (0.000)
Constant	−0.016 (0.022)	−0.022 (0.021)

*, P<0.05; **, P<0.01; ***, P<0.001. DEA, data envelopment analysis; SE, standard error; PHI, physician-hospital integration; FTE, full-time equivalent.

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