Case Study
ISSN: 3051-8830
Journal homepage: https://www.harrisonacademicpress.com/index.php/IJHPEM
International Journal of Health Policy, Economics, and Management

Harrison Academic Press

# Health Workforce Planning Models for Addressing Nursing Shortages: A Systems Dynamics Approach

**Makinen J[1*], Kask K[2] and Novak I[3]**

[1]*Department of Health Policy and Management, University of Helsinki, Helsinki, Finland*
[2]*Department of Public Health, University of Tartu, Tartu, Estonia*
[3]*Department of Human Resource Management, University of Zagreb, Zagreb, Croatia*

## ABSTRACT

*Background: Persistent nursing shortages threaten health system capacity worldwide, yet the dominant health workforce planning models forecast supply and demand as largely independent processes and cannot represent the feedback loops - burnout, turnover, and staffing adequacy - that empirical evidence shows to be central to how shortages emerge and persist. Objective: This case study synthesizes the literature on health workforce planning methodology, nurse retention and turnover, and applied systems dynamics (SD) case studies to evaluate what a systems approach adds to nursing workforce planning and to compare the relative leverage of retention, staffing-ratio, and education-pipeline policy interventions. Methods: A case study synthesis (not a systematic review with a registered protocol) drew on PubMed/MEDLINE, Web of Science, and Crossref-indexed peer-reviewed journal articles, each individually verified against its publisher or bibliographic database record, and organized thematically into three domains: descriptive and projection evidence on the global nursing shortage; comparative health workforce planning model methodology; and empirical evidence on the feedback mechanisms that SD models represent explicitly. Findings: Umbrella-review and cross-national survey evidence shows that burnout, turnover, and staffing adequacy function as mutually reinforcing rather than independent factors, a signature that static supply-projection and needs-based models cannot capture because they treat workforce behavior as an exogenous input. Applied SD case studies, most notably a validated national nurse supply model, demonstrate that representing the education pipeline, employed workforce, and working-condition feedback within a single coupled structure surfaces policy interactions - particularly the markedly different response delays of retention, staffing-ratio, and pipeline interventions - that are invisible to model families reconciling supply and demand only as a final comparative step. International migration further complicates single-country models by redistributing, rather than expanding, a constrained global nursing stock. Conclusions: Health workforce planners evaluating single interventions in isolation risk materially misestimating their effect on a coupled system; retention and staffing-ratio measures offer the fastest leverage on the reinforcing burnout-turnover loop, while education-pipeline expansion offers the largest eventual supply gain only after a multi-year delay. Wider adoption of systems dynamics modeling, supported by more validated cross-national case studies and transparent reporting of feedback structure, is needed to guide sequenced rather than single-lever nursing workforce policy.*

***Keywords:*** *nursing shortage; health workforce planning; systems dynamics modeling; nurse retention and turnover; staffing ratios*

**Citation:** Makinen J, Kask K and Novak I (2025) Health Workforce Planning Models for Addressing Nursing Shortages: A Systems Dynamics Approach. Int J Health Policy Econ Manag, 3(1): 01-07.
**DOI: 10.5281/zenodo.22656381**

**Corresponding Author:** *Juho Makinen*

**E-mail Address:** *juho.makinen@universityofhelsinki.edu*

**Article History:** *Received 4 January 2025 | Accepted 8 April 2025 | Published 27 June 2025*

**Copyright:** *© 2025 Juho Makinen, et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited (**https://creativecommons.org/licenses/by/4.0/**).*

## Introduction

Nursing shortages are not new, but the scale and persistence of the current shortfall distinguish it from earlier cyclical episodes. The World Health Organization's most recent reassessment of global health workforce stocks estimates a shortfall of roughly 10.2 million health workers by 2030, concentrated overwhelmingly in low- and lower-middle-income countries, with nursing personnel constituting the single largest occupational category within that gap [1]. High-income health systems are not exempt: even where aggregate projections of the licensed registered nurse workforce point toward continued numerical growth, hospitals across North America, Europe, and parts of the Asia-Pacific region report chronic bedside vacancy rates, rising reliance on temporary staffing agencies, and mandatory-overtime practices that themselves accelerate attrition — a divergence between licensed supply and deployable clinical capacity that growth projections alone do not resolve [2,3]. What makes the nursing workforce problem analytically distinctive is that it is not simply a deficit closed by producing more graduates; it is a

dynamic system in which the causes of shortage and its consequences are mutually reinforcing. Understaffing increases workload and burnout, burnout increases turnover intention and early exit, and the resulting vacancies deepen the understaffing that started the cycle [4,5].

Traditional health workforce planning models have struggled to capture this circularity. The dominant methodological tradition — supply projection models that extrapolate cohort flows through education pipelines and demand models that extrapolate population need from demographic and epidemiological trends — treats supply and demand as largely independent processes that planners reconcile after the fact [6,7]. This architecture answers "how many nurses will there be in ten years if current trends continue" reasonably well, but not "what happens if a staffing-ratio mandate is introduced, or if burnout-driven attrition rises by five percentage points." Because it omits the feedback pathways connecting working conditions back to supply, static projection underestimates the volatility of nursing labor markets and offers limited traction on the question of greatest practical interest: which interventions, in what combination, actually reverse a shortage once feedback loops have taken hold.

Systems dynamics (SD) modeling offers a methodological alternative purpose-built for problems of exactly this kind. Developed originally for industrial and corporate planning and subsequently adapted to public health applications including infectious disease control and health system capacity planning, SD represents a system as interconnected stocks (accumulations, such as the number of employed nurses), flows (rates of change, such as hiring and attrition), and feedback loops connecting flows back to stocks [8]. Applied to nursing, an SD model can represent simultaneously the education pipeline (enrollment, training attrition, licensure), the employed workforce (hiring, transfer, retirement, voluntary exit), and the working conditions that both result from and feed back into workforce size (staffing ratios, overtime, burnout, turnover intention). Early applications of this approach to nurse workforce projection, most notably in Malaysia, demonstrated that SD models can reproduce historical supply trends with reasonable fidelity while supporting scenario analysis of policy levers static models cannot represent at all [9].

This paper presents a case study synthesis of how systems dynamics modeling has been, and can be, applied to nursing workforce planning, integrating three previously disconnected literatures: health workforce projection methodology, the empirical literature on nurse retention and turnover, and applied SD case studies in health workforce and public health capacity planning. The Findings are organized around three themes: the global epidemiology of the nursing shortage and why it resists static projection; the comparative structure of workforce planning model families and what SD modeling adds; and the feedback-loop architecture SD models make visible, together with what simulated policy interventions targeting that architecture suggest about the relative leverage of retention, staffing-ratio, and pipeline-capacity policies. The objective is not to present a single validated simulation but to synthesize the case-study and methodological evidence into a coherent account of why a systems approach is needed here, and where the evidence base remains thin.

## Methods

This is a case study synthesis rather than a systematic review with a registered protocol, reflecting both the applied policy orientation of the topic and the heterogeneity of the underlying literature, which spans health services research, operations research, health economics, and health policy. Relevant literature was identified through targeted searches of PubMed/MEDLINE, Web of Science, and Crossref-indexed journals using combinations of terms including "system dynamics," "nurse workforce," "nursing shortage," "workforce planning model," "supply and demand," "turnover," "retention," "staffing ratio," "skill mix," and "health workforce projection." Candidate sources were restricted to peer-reviewed journal articles and were each individually verified against their publisher or bibliographic database record — author list, journal, volume/issue, pagination, and DOI — before inclusion; sources that could not be independently verified this way were excluded rather than retained on a plausible title alone.

Sources were organized thematically into three domains structuring the Findings section: (1) descriptive and projection literature on the scale, distribution, and drivers of the global nursing shortage; (2) comparative methodological literature on health workforce planning model families, including supply-projection, needs-based, and system dynamics approaches; and (3) empirical and case-study literature on the feedback mechanisms — burnout, turnover, staffing ratios, and education-pipeline constraints — that SD models represent explicitly and that competing model families typically treat as exogenous. Because included studies vary substantially in setting, time horizon, and outcome measurement, no attempt was made to pool quantitative findings into a single effect estimate; figures and tables synthesize illustrative, source-attributed values rather than a meta-analysis, consistent with prior methodological reviews finding that heterogeneity in model structure and reporting practice across this field precludes formal quantitative synthesis [7,6].

## The Nursing Shortage: Global Trends and Regional Disparities

The contemporary nursing shortage is best understood as a set of overlapping national and regional shortages with substantially different underlying drivers, not a single global phenomenon with a uniform cause. The WHO's National Health Workforce Accounts-based reassessment estimates the global health worker shortage fell from an earlier estimate of 18 million to approximately 15.4 million workers in 2020, with a projected further decline to 10.2 million by 2030 — but this aggregate improvement masks a highly uneven distribution, with high-income countries having a health worker density roughly 6.5 times that of low-income countries, and 47 countries on the WHO's support list expected to account for roughly 69% of the remaining 2030 shortfall [1]. Nursing personnel make up close to half of the global health workforce and are correspondingly central to this shortfall in absolute terms.

In high-income settings, the shortage manifests less as an absolute scarcity of trained nurses and more as a mismatch between the number of licensed nurses and the number willing to remain in bedside clinical roles under prevailing working conditions. Modeling of the disruptive labor-market effects of the COVID-19 pandemic on the United States nursing workforce found that pandemic-era hospitalization surges produced sharp increases in travel-nurse wage premiums alongside elevated exit rates from permanent hospital employment, effects that persisted well beyond the acute phase and left many systems with a smaller core workforce than before 2020 even as the total licensed stock

kept growing [3]. This divergence between licensed stock and the flow of nurses willing to remain in active practice is exactly what static supply-and-demand projection — which typically models licensure and retirement but not burnout-driven attrition or wage-responsive re-entry — is poorly equipped to anticipate.

***Categories of causal and consequential factors identified across systematic reviews of hospital nursing shortages, illustrating the overlap between factors classified as causes and as effects of shortage in the umbrella-review evidence (Jones and Allin, 2025).***




An umbrella review synthesizing 33 systematic reviews of the causes and effects of hospital nursing shortages found that a substantial share of the factors identified in the literature function as both causes and consequences of shortage: stress and burnout are documented as consequences of understaffing but also as predictors of subsequent staff attrition, and attrition in turn increases workload pressure on remaining staff, closing a self-reinforcing loop [4]. This finding is consistent with meta-analytic evidence on burnout prevalence among nurses, which estimates a pooled global prevalence of burnout symptoms of approximately 11%, with marked variation by region and clinical specialty, and with the broader turnover literature, which identifies managerial style, supervisory support, and workload as the organizational factors most consistently associated with voluntary exit [5,10]. Figure 1 summarizes the categories of causal and consequential factors identified across the reviewed umbrella-review evidence, illustrating the extent to which the same underlying conditions recur on both sides of the cause–effect ledger — the empirical signature of a feedback-driven system rather than a simple supply deficit.

International migration adds a further redistributive dynamic layered on top of these national shortages. Monitoring of the WHO Global Code of Practice on the International Recruitment of Health Personnel found that voluntary, non-binding ethical recruitment guidance raised awareness of source-country workforce vulnerability among destination-country policymakers but had only a modest, unevenly enforced effect on actual recruitment volumes, in part because destination-country domestic shortfalls generated recruitment incentives the Code's voluntary provisions could not fully offset [11]. Earlier comparative work similarly found that migration flows respond rapidly to relative wage and working-condition differentials between countries, so that a shortage-driven recruitment campaign in one high-income country can measurably deepen the shortage in the source countries it draws from [12]. Nursing workforce models confined to a single national boundary therefore risk mistaking a redistribution of a fixed or slow-growing global nursing stock for a genuine expansion of supply.

## Modeling Approaches to Health Workforce Planning: From Static Projections to System Dynamics

Systematic reviews of health workforce planning methodology identify a persistent typology of model families, distinguished chiefly by how they define adequacy of supply and whether they represent the interaction between supply and demand over time. One such review identified supply-projection, demand-based, needs-based, and "supply-and-demand" hybrid approaches as the dominant families, finding that most published models — including most nurse-specific applications — adopt some form of the hybrid approach, forecasting future supply largely independently of a separately forecast future demand and reconciling the two only as a final comparative step [6]. A parallel review of projection-modeling reporting practice found substantial inconsistency across published models in how key structural assumptions — attrition rates, productivity, and time horizon — are documented, complicating replication and cross-country comparison, and proposed a good-practice reporting guideline to make these choices more transparent regardless of model family [7].

***Structural comparison of health workforce planning model families reviewed here, highlighting the feedback representation that distinguishes the systems dynamics approach.***

| Model family | Core forecasting logic | Feedback between workforce conditions and supply | Typical time horizon | Key reference |
|---|---|---|---|---|
| Supply-projection | Extrapolates future stock from cohort flows through education, licensure, and retirement | Not represented; attrition and entry rates are exogenous assumptions | Medium to long term (10-20 years) | Bosak et al. 2023 |
| Needs-based / demand | Derives required workforce from population health need or projected service utilization | Not represented; required workforce is independent of working conditions | Medium term (5-15 years) | Lee et al. 2024 |
| Skill-mix / task-shifting | Reallocates tasks across occupational categories to relieve constrained categories | Partial; captures redistribution of workload but not behavioral attrition response | Short to medium term | Dubois and Singh 2009 |
| Discrete event simulation | Simulates shift-level patient demand and staff scheduling at high operational granularity | Not represented at the workforce-stock level; models staff availability, not long-run attrition or entry | Short term (shifts to months) | Simmons et al. 2025 |

| Model family | Core forecasting logic | Feedback between workforce conditions and supply | Typical time horizon | Key reference |
|---|---|---|---|---|
| Systems dynamics | Represents education pipeline, employed stock, and working-condition feedback as a single coupled structure | Explicit; staffing adequacy, burnout, and turnover are jointly and endogenously determined | Long term (10-20+ years), with explicit short-term feedback dynamics | Abas et al. 2018 |

Needs-based and demand-based models attempt to ground workforce requirements in population health need or projected service utilization rather than historical staffing patterns, and skill-mix and task-shifting research represents a related but distinct tradition treating workforce composition, not merely headcount, as the object of planning [13]. Evidence on task-shifting from physicians to nurses demonstrates that skill-mix reallocation can measurably relieve pressure on more constrained occupational categories, but overviews of this literature caution that its net effect on total workforce requirements, as opposed to redistribution across categories, remains limited, particularly for nursing tasks shifted to lower-skill categories such as nursing assistants [14]. What unites the supply-projection, demand-based, needs-based, and skill-mix traditions, despite real differences, is a common limitation: each treats the workforce's own behavioral responses — attrition in response to working conditions, entry and re-entry in response to wages, burnout propagation through overworked units — as external inputs rather than as outputs the model itself generates.

System dynamics modeling differs from this shared architecture in a specific way: it represents workforce size, working conditions, and workforce behavior as jointly and endogenously determined within a single closed-loop structure, so a policy intervention introduced anywhere propagates through every stock and flow to which it is connected. The applied case-study literature on SD nurse workforce models remains comparatively small relative to the supply-projection literature, but existing applications demonstrate the approach's distinguishing capability. The Malaysian national nurse supply model, built from three interacting sub-models covering training output, demographic change, and full-time-equivalent utilization, was validated against fifteen years of historical Ministry of Health data and used to test scenario interventions — expanded training intake, modified retirement policy — whose combined effects on the projected 2030 stock could not have been derived by summing each intervention's isolated effect, precisely because the sub-models are coupled through shared feedback pathways [9]. Table 1 compares the structural features of the model families reviewed here, highlighting the feedback representation that most clearly differentiates the SD approach.

Operations-research approaches such as discrete event simulation occupy an intermediate position in this comparison. A discrete event simulation built to determine nurse staffing for an Acute Care for Elders hospital unit modeled patient-level demand at a granular, shift-by-shift level and produced staffing recommendations sensitive to acuity mix in ways fixed ratio policies cannot replicate, but it modeled staff availability and scheduling constraints rather than the longer-horizon behavioral processes of burnout-driven attrition that SD modeling targets [15]. The two approaches are complementary rather than competing: discrete event simulation suits short-horizon operational staffing decisions within a fixed workforce, while system dynamics suits the longer-horizon question of how that workforce's size and composition evolve under alternative policy regimes.

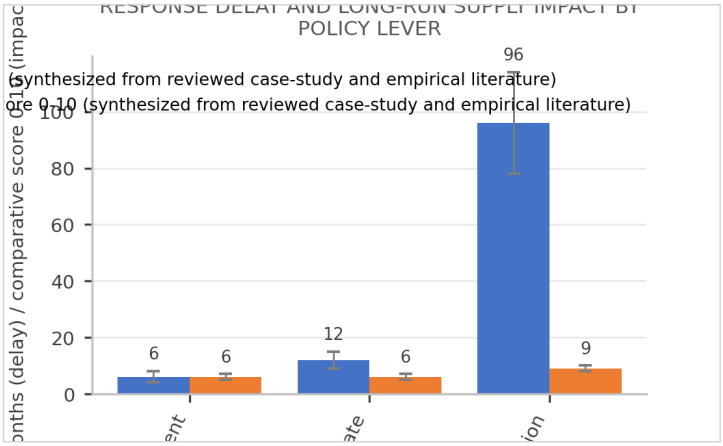
## Systems Dynamics Structure: Feedback Loops Driving Nursing Workforce Sustainability

The analytical value of representing the nursing workforce as a system of coupled feedback loops rather than a set of independent projections becomes clearest when the loops are made explicit. Drawing on the empirical literature reviewed above, four feedback structures recur across applied nurse workforce SD models and case studies, two reinforcing (self-amplifying) and two balancing (self-correcting).

The first and most consequential reinforcing loop connects staffing adequacy to burnout to turnover and back to staffing adequacy. Empirical evidence indicates that inadequate staffing measurably increases nurse burnout and job dissatisfaction, which predicts higher turnover intention and actual voluntary exit, which further reduces staffing adequacy for the nurses who remain [16,5,10]. Cross-national survey evidence spanning twelve countries in Europe and the United States found burnout prevalence ranging from roughly 10% to 78% depending on hospital work environment, with better staffing ratios and work environments consistently associated with lower burnout and higher-rated care quality — direct empirical support for treating staffing ratio and burnout as mutually reinforcing rather than independent variables [17]. A second reinforcing loop operates through the cost of turnover itself: replacing an experienced bedside nurse imposes recruitment, orientation, and lost-productivity costs conservatively estimated in the tens of thousands of dollars once inflation-adjusted, and systems facing budget pressure from high turnover frequently respond by constraining hiring or overtime budgets, further degrading the conditions driving the turnover in the first place [18].

Balancing loops, by contrast, represent stabilizing mechanisms that the reinforcing loops above can overwhelm if left unaddressed. The education pipeline functions as a balancing loop with substantial delay: increased enrollment, driven by wage/availability signals or by policy, eventually increases new-graduate supply, but the multi-year training period means this correction arrives only years later, during which the reinforcing burnout-turnover loop can continue to deepen the shortage largely unopposed [1]. Legislated staffing-ratio mandates represent a second, faster-acting balancing mechanism: a prospective panel study of nurse-to-patient ratio legislation found mandated minimum ratios measurably improved staffing levels and were associated with reduced mortality, fewer readmissions, and shorter length of stay relative to comparison hospitals, indicating that a regulatory floor on staffing can interrupt the reinforcing loop directly rather than waiting for pipeline-driven growth to catch up [19]. Figure 2 summarizes, in illustrative comparative terms drawn from the case-study and empirical literature reviewed above, how the two balancing mechanisms — staffing-ratio regulation and education-pipeline expansion — differ sharply in response delay and in long-run workforce-supply impact, a contrast developed further in the following section on simulated policy interventions [9,19].

***Illustrative comparison of response delay and long-run workforce-supply impact for three policy levers targeting the nursing workforce feedback system, synthesized from the case-study and empirical literature reviewed (Abas et al., 2018; McHugh et al., 2021; Jones, 2008).***




International migration overlays a fifth structural feature: a cross-border flow that can partially and rapidly offset a domestic shortage in a high-income destination country while deepening the equivalent shortage in a lower-income source country, without increasing the aggregate global supply of trained nurses [12,11]. National-level SD models that treat international recruitment as an exogenous supply addition, rather than as a stock transferred out of another country's coupled system, will systematically overstate the net global benefit of recruitment relative to nationally coordinated retention and pipeline investment.

## Simulating Policy Interventions: Retention, Staffing Ratios, and Education Pipeline Capacity

Because SD models render feedback structure explicit, they support a distinctive class of policy analysis: comparing not merely the isolated effect of a single lever but the combined and sequenced effect of multiple levers operating on a shared, coupled system. Three intervention categories recur across the reviewed evidence, and while a fully validated multi-country SD simulation of all three together does not yet exist in the published literature, the case-study and empirical evidence supports provisional conclusions about their relative and combined leverage.

Retention-focused interventions targeting the burnout-turnover reinforcing loop directly appear to offer the fastest leverage because they act on a loop with comparatively short response delay: improving staffing ratios, work-environment quality, and managerial support has been shown to reduce burnout and turnover intention within the same operational period the intervention is introduced, rather than after a multi-year lag [17,10]. The turnover-cost literature reinforces the economic case: because replacing a departed nurse costs substantially more than retaining one, resources redirected from recruitment and agency budgets toward retention investment can in principle be self-financing over a multi-year horizon [18]. A national retention study in underserved areas of Lebanon similarly found facility-level investment in supervisory support and career development associated with higher retention than compensation adjustments alone, suggesting the organizational rather than purely financial dimensions of the loop are where retention interventions exert their fastest effect [20].

Staffing-ratio mandates act on the same reinforcing loop through regulatory rather than organizational mechanisms; the prospective panel evaluation of ratio legislation found measurable improvements in both staffing levels and patient outcomes following implementation [19]. The literature nonetheless flags an important caveat: a ratio mandate introduced without a corresponding pipeline or retention response can, in a system already near its supply ceiling, simply redistribute a fixed nursing stock across facilities rather than expanding it — an outcome a model representing only the mandated units, and not the coupled labor market it draws staff from, would fail to anticipate.

Education-pipeline expansion acts on the balancing loop with the longest delay and, on the evidence reviewed, the largest eventual capacity but the least short-term responsiveness. The Malaysian SD model's scenario analysis of expanded training intake illustrates this trade-off: increased enrollment measurably raised the projected long-run stock, but the multi-year training and licensure pipeline meant the improvement was not fully realized until roughly a decade after the policy change, during which burnout-and-turnover-driven attrition could continue eroding adequacy unless paired with concurrent retention measures [9]. This is consistent with broader review evidence that models incorporating explicit pipeline-delay structures produce more conservative near-term forecasts than models treating pipeline expansion as immediately effective [7,6].

Taken together, the evidence supports a sequenced rather than either/or interpretation: retention and staffing-ratio interventions offer the shortest-delay leverage and are best positioned to arrest a deepening shortage near-term, while pipeline expansion offers the largest eventual gain only after a multi-year delay during which the reinforcing loop must be independently contained. A systems dynamics framework's principal contribution is not a single optimal intervention but the demonstration that these levers interact rather than substitute for one another, so evaluating any lever in isolation — standard practice under static projection — risks materially misestimating its net effect on the coupled system.

## Discussion

Three general conclusions follow from this case-study synthesis. First, the empirical signature of the contemporary nursing shortage — in which burnout and turnover recur as both causes and consequences across the reviewed umbrella-review and cross-national survey evidence — is precisely the signature a feedback-driven system produces, and is not well explained by models that treat supply and demand as independently forecastable [4,17]. Second, applied SD case studies, though limited in number relative to the broader projection literature, demonstrate a reproducible methodological advantage: representing pipeline, stock, and working-condition feedback within one coupled model surfaces policy interactions — such as the differential response delay of retention versus pipeline interventions — invisible to model families that reconcile supply and demand only as a final comparative step [9,6]. Third, the cross-border migration evidence indicates that any national-level model treating international recruitment as a costless external supply addition will systematically overstate its net benefit relative to domestic retention and pipeline investment, because migration principally redistributes rather than expands the global nursing stock [12,11].

These findings carry direct policy implications. Policymakers evaluating a single intervention — a staffing-ratio mandate, an enrollment expansion, a retention bonus program — in isolation should treat that evaluation as a lower bound, since each lever's

effectiveness is conditional on the state of the coupled system it operates within; a ratio mandate introduced into a system near its supply ceiling risks redistributing scarcity rather than resolving it unless paired with retention or pipeline measures [19,9]. For modelers, good-practice reporting recommendations — explicit documentation of attrition assumptions, time horizon, and feedback structure — apply with particular force to SD applications, where the causal loop structure is the model's central analytic contribution [7].

This synthesis has limitations. As a case study synthesis rather than a systematic review with a registered protocol, the search cannot claim exhaustive coverage, and the applied SD nurse workforce literature remains sparse enough that conclusions rest substantially on a small number of national case studies rather than a large corpus of replicated models. The quantitative findings drawn from individual studies — burnout prevalence, turnover cost, staffing-ratio outcomes — are heterogeneous in population and method and are presented as illustrative of directional patterns rather than pooled estimates. Finally, because nursing labor markets and their policy responses have evolved rapidly since 2020, conclusions drawn from earlier studies may understate dynamics that have since intensified or partially resolved.

## Conclusion

The nursing shortage confronting health systems worldwide is a feedback-driven phenomenon in which working conditions, burnout, turnover, and workforce supply are mutually determining rather than independently forecastable quantities. Health workforce planning models built on the dominant supply-projection and needs-based traditions, while methodologically mature and well suited to long-range aggregate forecasting, structurally omit the behavioral feedback pathways that the empirical retention, burnout, and staffing-ratio literature shows to be central to how shortages actually emerge and persist. Systems dynamics modeling addresses this gap by representing the education pipeline, employed workforce, and working-condition feedback within a single coupled structure, and the limited but instructive case-study evidence available — most clearly the Malaysian national nurse supply model — demonstrates that this approach surfaces policy interactions, particularly the differing response delays of retention, staffing-ratio, and pipeline interventions, that static projection cannot represent. Realizing its full potential will require a substantially larger base of validated, cross-nationally comparable SD case studies than currently exists, together with modeling practice that treats international migration as a genuine cross-border transfer within a global coupled system rather than a costless local supply addition. Until that evidence base matures, health workforce planners should treat single-lever policy evaluations with caution and prioritize combinations of retention, staffing-ratio, and pipeline-capacity investment sequenced according to the response delay each lever's underlying feedback loop actually exhibits.

## References


1. Boniol M, Kunjumen T, Nair TS, Siyam A, Campbell J, Diallo K (2022) The global health workforce stock and distribution in 2020 and 2030: a threat to equity and 'universal' health coverage? BMJ Global Health, 7(6):e009316, DOI:10.1136/bmjgh-2022-009316.
2. Auerbach DI, Buerhaus PI, Staiger DO (2017) How fast will the registered nurse workforce grow through 2030? Projections in nine regions of the country. Nursing Outlook, 65(1):116-122, DOI:10.1016/j.outlook.2016.07.004.
3. Vardavas R, Nascimento De Lima P, Baker L, Crowley C, Carman K, Parker AM, Abir M (2026) Modeling the disruptive impact of the COVID-19 pandemic on nurses' supply and wages. Frontiers in Epidemiology, 6:1631582, DOI:10.3389/fepid.2026.1631582.
4. Jones D, Allin S (2025) Causes and effects of hospital nursing shortages to consider potential feedback effects: an umbrella review. Human Resources for Health, 23:61, DOI:10.1186/s12960-025-01028-w.
5. Woo T, Ho R, Tang A, Tam W (2020) Global prevalence of burnout symptoms among nurses: a systematic review and meta-analysis. Journal of Psychiatric Research, 123:9-20, DOI:10.1016/j.jpsychires.2019.12.015.
6. Bosak S, Yazdani S, Ayati MH (2023) Approaches and components of health workforce planning models: a systematic review. Iranian Journal of Medical Sciences, 48(4):358-369, DOI:10.30476/ijms.2022.94662.2600.
7. Lee JT, Crettenden I, Tran M, Miller D, Cormack M, Cahill M, Li J, Sugiura T, Xiang F (2024) Methods for health workforce projection model: systematic review and recommended good practice reporting guideline. Human Resources for Health, 22:25, DOI:10.1186/s12960-024-00895-z.
8. Homer JB, Hirsch GB (2006) System dynamics modeling for public health: background and opportunities. American Journal of Public Health, 96(3):452-458, DOI:10.2105/AJPH.2005.062059.
9. Abas ZA, Ramli MR, Desa MI, Saleh N, Hanafiah AN, Aziz N, Abidin ZZ, Shibghatullah AS, Rahman AFNA, Musa H (2018) A supply model for nurse workforce projection in Malaysia. Health Care Management Science, 21(4):573-586, DOI:10.1007/s10729-017-9413-7.
10. Halter M, Boiko O, Pelone F, Beighton C, Harris R, Gale J, Gourlay S, Drennan V (2017) The determinants and consequences of adult nursing staff turnover: a systematic review of systematic reviews. BMC Health Services Research, 17:824, DOI:10.1186/s12913-017-2707-0.
11. Siyam A, Zurn P, Ro OC, Gedik G, Ronquillo K, Co CJ, Vaillancourt-Laflamme C, dela Rosa J, Perfilieva G, Dal Poz MR (2013) Monitoring the implementation of the WHO Global Code of Practice on the International Recruitment of Health Personnel. Bulletin of the World Health Organization, 91(11):816-823, DOI:10.2471/blt.13.118778.
12. Aiken LH, Buchan J, Sochalski J, Nichols B, Powell M (2004) Trends in international nurse migration. Health Affairs, 23(3):69-77, DOI:10.1377/hlthaff.23.3.69.
13. Dubois CA, Singh D (2009) From staff-mix to skill-mix and beyond: towards a systemic approach to health workforce management. Human Resources for Health, 7:87, DOI:10.1186/1478-4491-7-87.
14. Paier-Abuzahra M, Posch N, Jeitler K, Semlitsch T, Radl-Karimi C, Spary-Kainz U, Horvath K, Siebenhofer A (2024) Effects of task-shifting from primary care physicians to nurses: an overview of systematic reviews. Human Resources for Health,

22:74, DOI:10.1186/s12960-024-00956-3.

15. Simmons SF, Hollingsworth EK, Slagle JM, Kim J, Wilson L, Shah A, Duggan MC, Schnelle JF (2025) An objective method to determine nurse staffing for an Acute Care for Elders (ACE) hospital unit: discrete event simulation. Journal of the American Geriatrics Society, 73(7):2146-2154, DOI:10.1111/jgs.19507.

16. Aiken LH, Clarke SP, Sloane DM, Sochalski J, Silber JH (2002) Hospital nurse staffing and patient mortality, nurse burnout, and job dissatisfaction. JAMA, 288(16):1987-1993, DOI:10.1001/jama.288.16.1987.

17. Aiken LH, Sermeus W, Van den Heede K, Sloane DM, Busse R, McKee M, Bruyneel L, Rafferty AM, Griffiths P, Moreno-Casbas MT, Tishelman C, Scott A, Brzostek T, Kinnunen J, Schwendimann R, Heinen M, Zikos D, Sjetne IS, Smith HL, Kutney-Lee A (2012) Patient safety, satisfaction, and quality of hospital care: cross sectional surveys of nurses and patients in 12 countries in Europe and the United States. BMJ, 344:e1717, DOI:10.1136/bmj.e1717.

18. Jones CB (2008) Revisiting nurse turnover costs: adjusting for inflation. Journal of Nursing Administration, 38(1):11-18, DOI:10.1097/01.NNA.0000295636.03216.6f.

19. McHugh MD, Aiken LH, Sloane DM, Windsor C, Douglas C, Yates P (2021) Effects of nurse-to-patient ratio legislation on nurse staffing and patient mortality, readmissions, and length of stay: a prospective study in a panel of hospitals. The Lancet, 397(10288):1905-1913, DOI:10.1016/S0140-6736(21)00768-6.

20. El-Jardali F, Alameddine M, Jamal D, Dimassi H, Dumit NY, McEwen MK, Jaafar M, Murray SF (2013) A national study on nurses' retention in healthcare facilities in underserved areas in Lebanon. Human Resources for Health, 11:49, DOI:10.1186/1478-4491-11-49.