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ORIGINAL ARTICLE

Theoretical System Dynamics Modeling for Taiwan Pediatric Workforce in an Era of National Health Insurance and Low Birth Rates

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Background: In an era of declining birth rates and a single-payer health care system, the pediatric workforce might overreact to its demands. System dynamics (SD) were therefore applied to establish models to predict the future need and demand for the pediatric workforce.

Materials and methods: Data of population and workforce were extracted from national databases and models developed using Vensim software.

Results: In the past decade, the child-to-pediatrician ratio correlated with infant mortality in Taiwan ($p < 0.001$, $r^2 = 0.88$, child-to-pediatrician ratio $= 146 + 354 \times$ infant mortality/1000 live births). Currently, the child-to-pediatrician ratio is 1742:1. Using the Millennium Development Goals (2.437/1000 live births) for infant mortality, the child-to-pediatrician ratio was estimated as 1009:1. The pediatric population model incorporated the birth and mortality rates in each age category, accurately predicted population changes between 1974 and 2010, and projected a decreasing trend until 2017. The pediatric workforce model, which considered rates of enrollment, completion, certification, and retention, predicted a decrease in the supply of pediatricians in the mid-2010s that could be delayed by policy incentives. When targeting the base scenario, the model indicated that discrepancies between demands and supply of pediatricians would occur in the late 2010s toward 2020. When targeting the Millennium Development Goals scenario, however, the discrepancies would be consistent.

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Conclusion: Effective SD models were developed for the population and health care workforce. The strengths of the SD models are derived from simulation, which is subject to influence from new policies. Policies can, therefore, be examined and intervened in a timely manner.

1. Introduction

Pediatrics (a specialty established approximately 200 years ago) is the branch of medicine that is responsible for the health care of the pediatric population.[1,2] As of December 2010, there were 99,258 certified pediatricians in the USA with a child-to-pediatrician ratio of 1462:1.[3] The Future of Pediatric Education II estimated that approximately 3000 pediatricians entering residency are required annually to achieve projected workforce requirements.[4] The most suitable child-to-pediatrician ratio remains unclear. Its estimation is problematic because of diversity in types of pediatric health care practice among countries. For example, in countries following the UK medical system, family physicians provide most of the pediatric health care and pediatricians are used for referral and consultation. By contrast, in countries such as the USA, Japan, and Taiwan, pediatricians participate more extensively in primary care for children; therefore, the optimal child-to-pediatrician ratio is lower than in countries following the UK system.[5]

Taiwan initiated its pediatric postgraduate program in the 1960s. In 2010, the pediatric population was 4,595,767 and accounted for 19.8% of the entire population. Within the past decade, Taiwan has encountered declining birth rates and its birth rate in 2010 was the world's lowest. This has decreased the pediatric population and its medical requirements might, thus, show an associated decline. In Taiwan, 23 academic medical centers, 80 regional hospitals, and 435 district hospitals and nationwide primary pediatrics clinics serve to maintain child health. The child health care indices in Taiwan, including newborn mortality, infant mortality, under-5 mortality, and the mortality of the population aged 1–18 years, are comparable with those in the USA.[6] In 1995, Taiwan implemented a nationwide National Health Insurance program that covered more than 98% of the population. The system has been esteemed as a very successful national insurance system.[7] However, with limited resources of its single-payer system, the pediatric workforce is likely to exceed the requirements of the declining pediatric population.[8] A delay between new enrollment and the maturation of a workforce might also conceal a workforce shortage.

System dynamics (SD) is derived from the principles of cybernetics, information theory, decision theory, and computer simulation, and applies dynamic feedback perspectives to establish models for policy proposals that can effectively elucidate the structures of problems, interactions among various factors, processes, and feedback mechanisms.[9,10] SD is an analytical approach for representing complex human systems and predicting trends in data over time.[10] Simulations based on SD models, consisting of equations for flows and parameters, are developed to represent unique scenarios, and SD has been applied to analysis related to chronic diseases and workforce.[11–14] Therefore, in this study, we adopted an SD approach to develop models for the population and pediatric workforce to incorporate the multiple inputs and their relations into the equations for each stock and flow. Thereby, the gaps between needs and supply of pediatric workforce in the future may be predicted. Any intervention attempt can also be examined by changing the variables followed by simulation.

2. Materials and Methods

2.1. Data sources and collection

We defined the pediatric population as those aged <20 years. We obtained annual data on birth and mortality rates in infants, children aged 1–5 years, and then every 5 years from the national vital statistics from the Department of Health, Executive Yuan, Taiwan. We obtained data on the pediatric workforce from the databases of the Taiwan Pediatric Association and the Taiwan Medical Association. We defined certified pediatricians as those who had achieved pediatric certification after completion of 3 years' residency. We defined practicing pediatricians as the certified pediatricians who were registered with the Taiwan Medical Association.

2.2. System dynamics analysis

Using the SD approach, we may move away from looking at isolated events and their causes (usually assumed to be some other events), and start to look at the scenario as a system made up of interacting parts. The SD model is an interconnected system of differential equations that could be simulated on varying the input of variables. The state or stock variables in these equations include population subgroups in age category (for population model) or in pediatrician career stages (for pediatrician model). The initial values for the stocks were specified from historical data. The algebraic equations describe how the various flows into and out of the stocks are determined as well as the numerical estimates in these equations. After establishing the models, simulation could be made, calculating through the entire set of equations and updating the stock variables through small increments of time, until the final simulation time was reached, often decades into the future. SD simulation models help policymakers understand the impact of different interventions and potential leverage. To test an intervention, we only need to change the corresponding input to the model and perform another simulation.

SD was used to: (1) describe the scenario and identify the stock/flow; (2) develop mathematical models; and (3) conduct computer simulations. Simulation was performed to predict outcomes. Analyses used Vensim PLE software, version 5.11A (Ventana Systems, Harvard, MA, USA).

3. Results

3.1. Part I: Historical and current pediatric workforce

As of December 2010, there were 3329 (73% men) certified pediatricians in Taiwan. The mean age was 47.3 ± 10.4 years and the female pediatricians were significantly younger than male pediatricians (42.7 ± 8.4 years vs. 49.0 ± 10.5 years, $p < 0.001$). Of these pediatricians, 3004 had registered with the local medical association and participated in child health care. The overall child-to-pediatrician ratio was 1742:1 for people aged <20 years. The average percentage of certified applicants was approximately 84% (range, 75—90%). In the 2000s, we observed that the numbers of new and certified pediatricians showed declining trends. Because of declining birth rates, the pediatric population decreased from 7,321,837 in 1990 to 5,232,465 in 2010. We were able to estimate the medical requirements of the pediatric population according to population changes. We analyzed data from the most recent decade to evaluate the association between current infant mortality and the child-to-pediatrician ratio. For birth rates of 4—7/1000 live births, we identified a linear association between child-to-pediatrician ratio and infant mortality rate ($p = 0.000$, $r^2 = 0.89$, child-to-pediatrician ratio $= 146 + 354 \times$ infant mortality/1000 live births).

3.2. Part II. System dynamic analysis

3.2.1. Modeling process

3.2.1.1. Model 1: Scenario, variables, and interactions

As shown in Figure 1, SD analysis provided causal loop and stock and flow diagrams that illustrate the scenarios and variables that affect the flow of the pediatric workforce. In causal loop, a link from one element A to another element B is positive (+) if either (1) A adds to B or (2) a change in A produces a change in B in the same direction. However, a causal link from one element A to another element B is negative (−) if either (1) A subtracts from B or (2) a change in A produces a change in B in the opposite direction. The pediatric workforce includes hospital pediatric staff and primary care pediatricians who provide care to patients in an outpatient clinical setting. However, only the hospital staff is responsible for the health care of admitted patients and patients requiring emergency treatment. In teaching hospitals, under the supervision of attending physicians, residents (R1, R2, R3, and fellows, i.e., R4 and R5) provide care for patients in hospitals during their pediatric residencies or subspecialty fellowships. In circumstances of limited, or an absence of, residents, the attending physicians perform their duties. This can have a direct negative effect on career changes from hospital staff to primary care pediatrician.

3.3. Model 2: Population model and demands for pediatricians

An SD model was developed to predict the pediatric population and their medical requirements. The stock variables in this model include population subgroups in age category as well as the input from birth rate and mortality rate, which were obtained from Part I of the study. Because

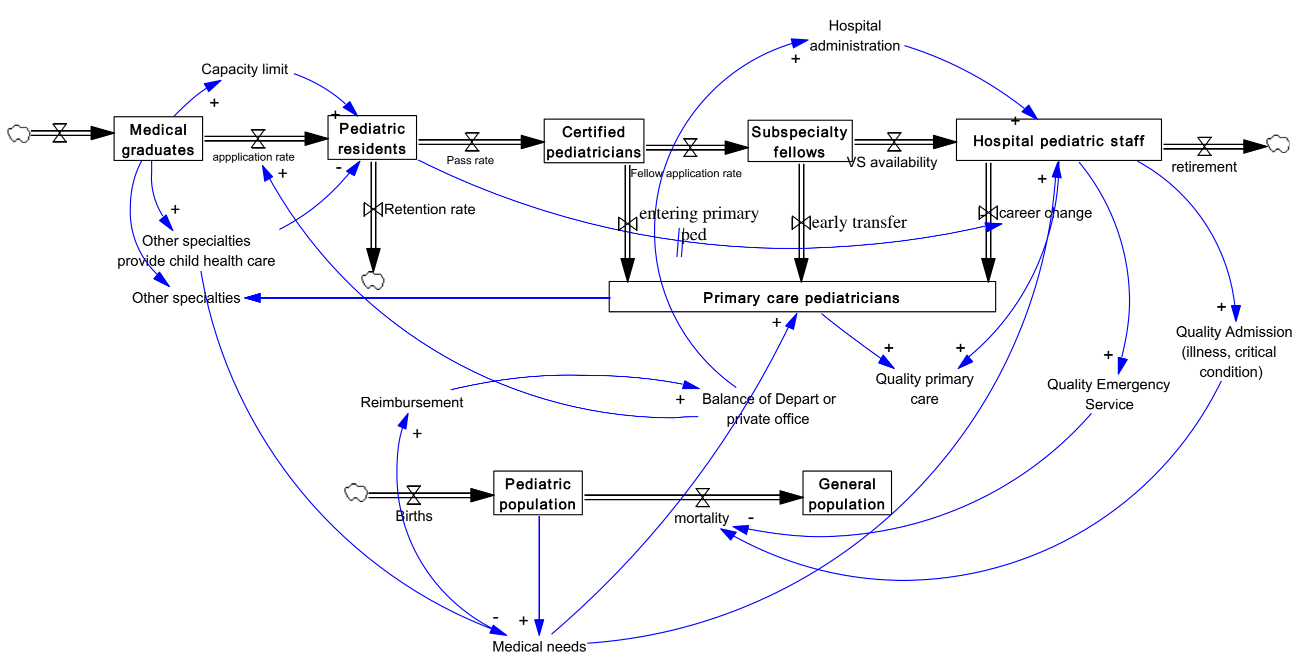

Figure 1 The system dynamic model for the scenarios and variables that affect the flow of the pediatric workforce.

deaths occur primarily during infancy and then decline gradually to a nadir at age 10–11 years, the pediatric population was categorized into the following stocks: infants (age <1 year), age 1–4 years, and then every 5 years (Figure 2). The example equation for the stock was Integral [Newborn rate − Infant grown up/year − Infant mortality/year]. Pediatricians provide care for infants and the population aged 1–19 years, and the population aged 15–49 years is responsible for childbearing. We defined the general fertility rate as the number of live births/1000 fertile women. We determined the flow rate according to the mortality rate in each category and were then able to estimate the pediatric population and the subsequent demands for pediatricians.

3.4. Model 3: Pediatric workforce model

The model consisted of four stocks: (1) residents in a pediatric residency program (3 years); (2) subspecialty fellows in a subspecialty program (2 years); (3) hospital staff; and (4) primary care pediatricians. Pediatric residents are eligible for certification following the successful completion of 3 years' training. Having passed the written and oral examinations for certification, they receive their pediatrics diplomas. Certified pediatricians serve in primary pediatric clinics or continue their subspecialty training for a further 2 years (Figure 3). The stock variables in this model include pediatrician career stages as well as the input from enrollment rate, certification rate, and the rate for each career change, which were obtained from Part I of the study. Pediatric residents can change their specialty training to other specialties, typically during the first year. Currently, there are 11 pediatric subspecialties including cardiology, immunology, critical care, emergency service, endocrinology, gastroenterology, genetics, infectious disease, nephrology, neurology, and pulmonology. Following subspecialty training, pediatricians can apply for an open hospital staff position or become a primary pediatrician. Hospital staff can remain in hospital until the age of retirement (65 years) or they may leave the hospital and become primary pediatricians, particularly in the regional hospitals. The example equation was Integral [Certified Ped Sub transfer rate + Departure rate + Early leaving rate + Transfer rate-career change − Retire rate] for the primary pediatricians, and Integral [Join hospital rate− Departure rate− Retire rate] for hospital staff. Data used in these models included the primary data collected during Part I of this study as well as some secondary data obtained from the national databases of the Taiwan Pediatric Association and the Taiwan Medical Association. These data and the equations for each flow and stock may be seen on the computer when the Vensim software is downloaded and the file opened in the .mdl format.

3.5. Simulation

3.5.1. Pediatric population and workforce demand

We validated the pediatric population model by examining the differences between actual data and the predicted population from 1974 to 2010. These differences were insignificant (Figure 4). Our results indicate that the future pediatric population will continue to decrease until 2017. We performed simulation based on two scenarios: base and Millennium Development Goals (MDG, the eight international development goals that were officially established following the Millennium Summit of the United Nations in 2000; MDG 4 was to decrease the infant mortality by two-thirds from 1990 to 2015). We defined the base scenario as infant mortality decreasing only by 0.5/1000 (i.e., 4.0/1000 live births). The MDG scenario would be 2.437/1000

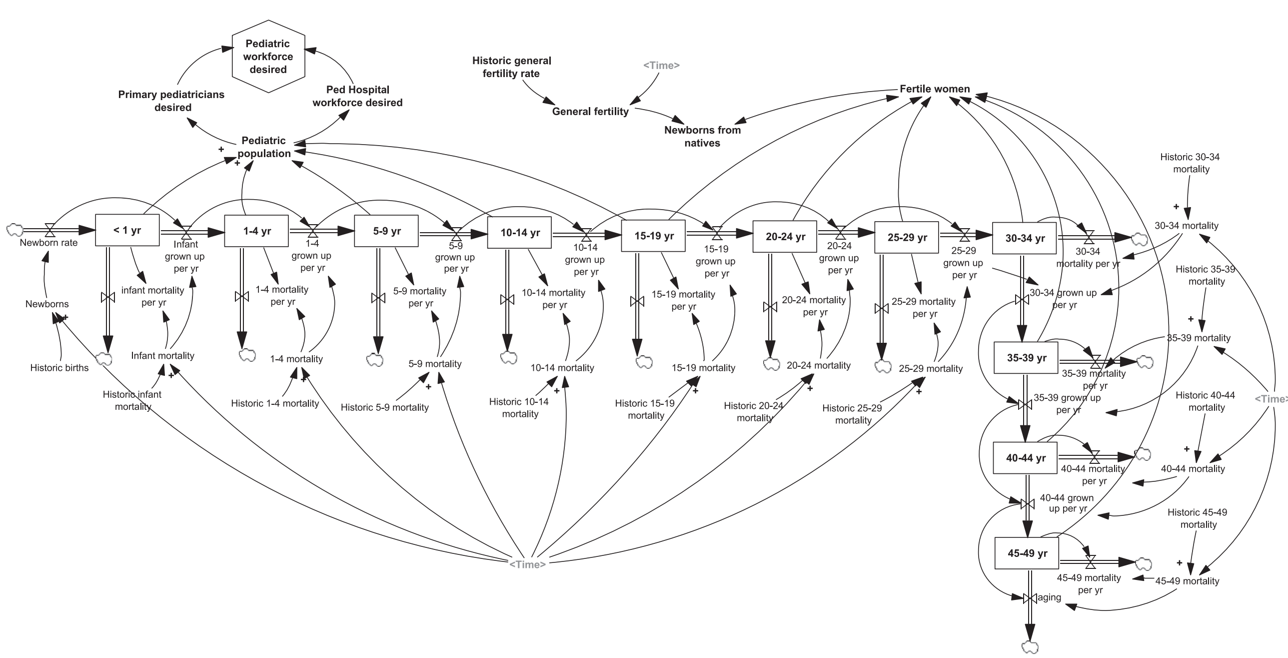

Figure 2 The system dynamic model of population and the demand of pediatricians.

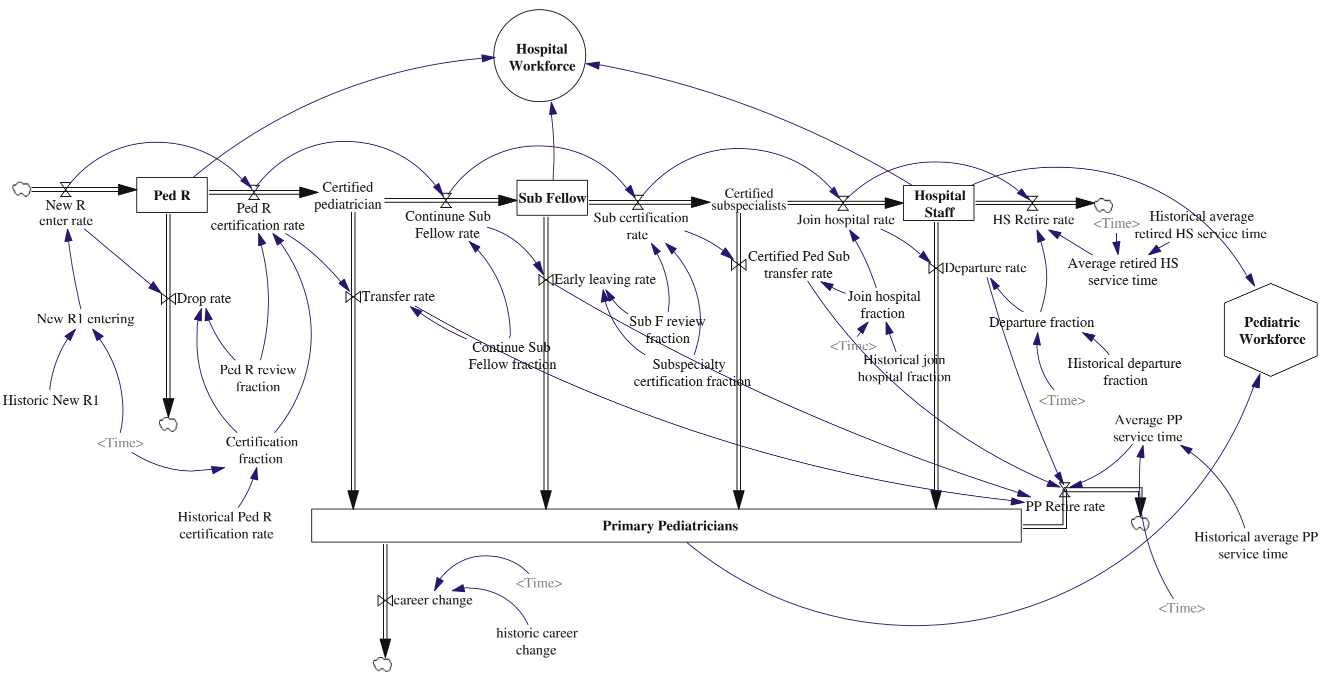

Figure 3 The system dynamic model of pediatric workforce. HS = hospital staff; Ped = pediatric; PP = primary pediatrician; R = resident; Sub F = subspecialty fellow.

live births. Based on the association between child-to-pediatrician ratio and infant mortality rate identified in Part I of our study, the required child-to-pediatrician ratio would be 1562:1 and 1009:1 for base and MDG scenarios, respectively. Figure 5 displays the predictions for demands for pediatricians in both scenarios. The demand for pediatricians would decrease with a declining pediatric population caused by low birth rates. Predicted demands for pediatricians in base/MDG scenarios are 2942/4555 in 2015, 2601/4069 in 2020, and 2432/3772 in 2030, respectively.

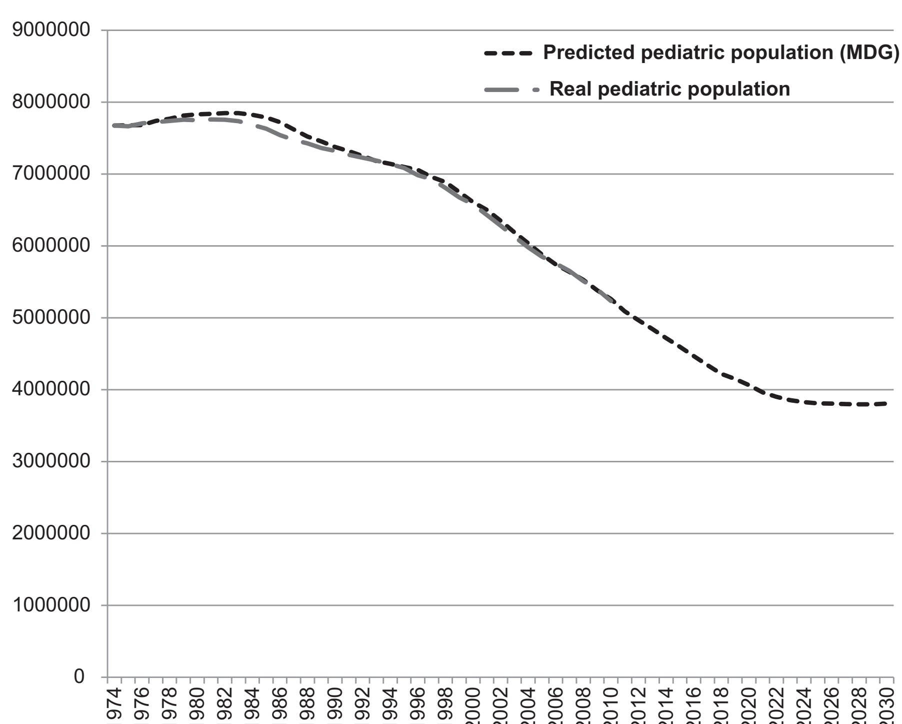

Figure 4 The population from 1974 to 2030 predicted from the system dynamics model established in this study and the real population from 1974 to 2010.

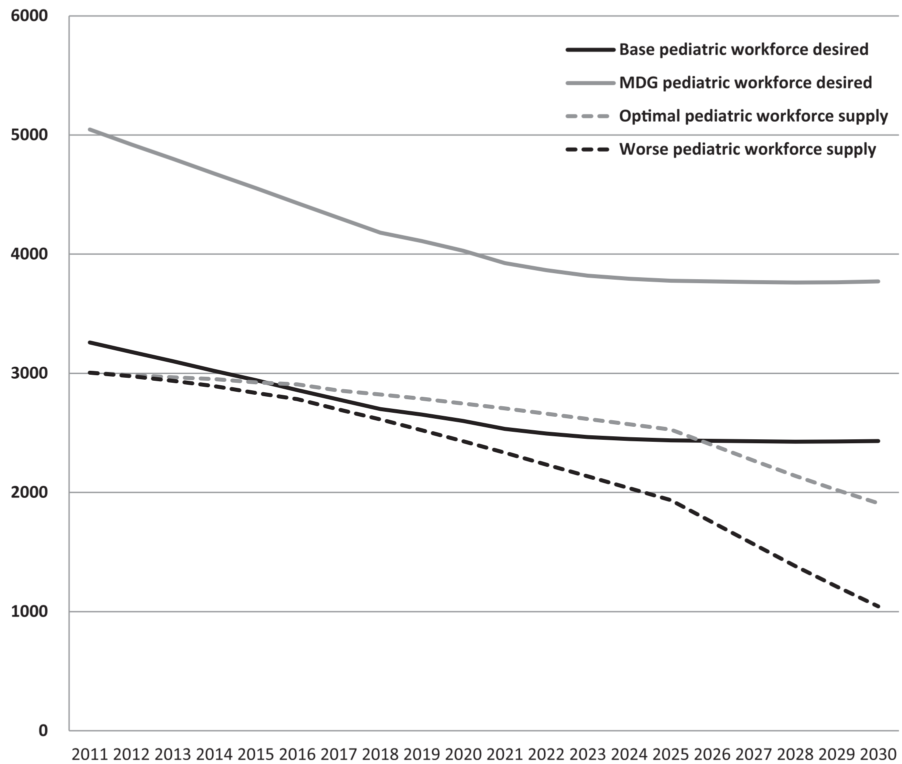

Figure 5 The prediction for the demand (base scenario and Millennium Development Goals scenario) and supply (optimal and worst scenario) of pediatricians.

3.6. Pediatric workforce supply

Using the model for simulation, the pediatric workforce during optimal and worst-case scenarios was estimated. The optimal scenario was assigned as an arrested trend for decline, because of promotional policy, and all parameters remaining stable over the ensuing 20 years, including the percentage of medical school graduates opting for pediatric residency, the proportion of residency reviews and certifications, the proportion of continuing subspecialties and certifications, and the proportion of hospital departures. The worst-case scenario was assigned as the continuation of a decreasing trend in resident enrollment until 2016, reaching a nadir of 50. The model predicted that 10 pediatricians would change their career to other medical services annually from 2012 onwards, reaching a maximal of 60 in 2014. As shown in Figure 5, in 2010, there were 3004 practicing pediatricians in Taiwan (Taiwan Medical Association data) and the model estimated the pediatrician workforce as 3019. Both the demand for and supply of pediatricians decreased within the year. However, post-2020, the decline in the pediatric workforce is likely to occur more rapidly, with discrepancy between supply and demand occurring within the late 2010s. With a positive incentive policy, the workforce could be optimized to delay any discrepancies between supply and demand. In the MDG scenario, the workforce in each situation was inadequate during all years.

4. Discussion

In an era of declining birth rates and national health insurance (i.e., a single-payer health care system) the pediatric workforce is challenged by decreasing medical requirements from a decreasing pediatric population. In this study, we established a population model to predict future changes in the pediatric population based on birth and mortality rates and the association between fertile adults and the numbers of births. We also established a model for the career paths of the pediatric workforce. Simulation enabled us to predict supply and demand in each scenario. This could provide an important tool for the optimization of policy-making concerning the health care workforce.

Several previous studies have investigated the pediatric workforce, including factors on career choices, geographic maldistribution highly skewed in favor of large cities and against rural areas, and discrepancy between supply and demand.[3,15–20] The percentage of medical students who select pediatrics as a career (enrollment rate) is typically in the range of 10–13%.[4,21] In a nationwide single-payer health care system, such as in Taiwan, intergenerational justice can further affect the pediatric workforce and distort reimbursement.[22] Subsequent effects on the sustainability of the pediatric workforce will become apparent only after significant delay. Given such a complex scenario, strategic dynamic thinking, such as the SD approach, could provide a useful means of predicting future outcomes. A recent study suggested the potential of modeling and simulation to predict the cardiac surgical workforce.[14] Investigators introduced the concept of SD during the 1950s and have extensively applied it in recent decades.[10–14] SD applies dynamic feedback perspectives to establish models for policy proposals that can effectively elucidate the structures of problems, interactions among various factors, processes, and feedback mechanisms.

Pediatrics is a specialty that provides care for the pediatric population. The physiology and disease categories of the pediatric population differ from those of adults. Premature babies represent the extreme of immature adaptation. Since the establishment of this specialty approximately 200 years ago, child health has improved progressively. Our data suggested a close association between child-to-pediatrician ratio and infant mortality in the range of 4/1000 live births to 7/1000 live births. In Japan, in 2004, infant mortality and the child-to-pediatrician ratio were 2.8:1 and 1190:1, respectively.[5] According to our study equation (expected child-to-pediatrician ratio $= 146 + 354 \times$ infant mortality), the expected child-to-pediatrician ratio would be 1137:1 for an infant mortality of 2.8; thus, the difference between the actual and derived number is minimal. It is, therefore, feasible to apply this equation to the SD model to estimate future demands for pediatricians. The MDG assigned by the United Nations was to reduce child mortality rates by two-thirds between 1990 and 2015 (Goal 4).[23] Prior to the initiation of the National Health Insurance (1995), infant mortality was underestimated in Taiwan; therefore, we assigned the MDG as a decrease from 7.311/1000 live births in 1995 to 2.437/1000 live births in 2015. Our model simulation revealed discrepancies between the demand for and supply of pediatricians in the late 2010s, targeting only the base scenario. Targeting the MDG infant mortality, the predicted discrepancies would be consistent and of higher significance. With optimal workforce scenario from positive incentive, the gap between the demand and supply would be delayed and could be filled by late interventions. Therefore, a timely policy for optimal workforce scenario is mandatory. With a single-payer system and a declining birth rate and pediatric population, the numbers of new residents and new pediatricians would also decrease. Deficits in the supply of pediatricians can become apparent only after a delay and are potentially irreversible. Although countries with a multipayer system might face similar problems in workforce supply, a single-payer system is likely to increase the severity of the problem.[24] Our SD models provide a means of simulating and predicting outcomes. Following the proposal of policies with positive incentives, resimulation of the SD models could facilitate the prediction of the effectiveness of interventions. Prediction and simulation by such SD models could potentially be equally effective if applied to other health care workforces.

The relationship between proportion of pediatric population and the number of pediatricians varies with contemporary medical care. In this study, only the influence from the size of pediatric population and the expected quality of pediatric care were used as the determinants of workforce needs. The current model did not include input variables such as changes in economic status, health outcome, hospital beds, disease complexity, and subsequent special workforce required, and the shift in population due to migration.[25] Nevertheless, when these data are available, the current SD models can be modified easily by additional input variables and repeated simulation can be performed to refine public policies.

In conclusion, in this study, we developed effective system dynamics models for the pediatric population and health care workforce to predict future paradigms. The strengths of the system approach and models are derived from simulation, which is subject to influence from new policies. Policies can, therefore, be examined and interventions can be made in a timely manner.

Financial disclosures

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