Workforce Modeling for the National Institutes of Health (NIH)

J. Chris White

viaSim

519 Interstate 30, #247

Rockwall, TX 75087

U.S.

972-722-9255 (tel)

972-722-9407 (fax)

jcwhite@viasimcorp.com

Margaret Rush

University of Virginia

303 Old Short Hills Road

Short Hills, NJ 07078

U.S.

973-568-4542

mlr5u@virginia.edu

Walter T. Schaffer, Ph.D.

Senior Scientific Advisor for Extramural Research

Office of Extramural Research

National Institutes of Health

Building One, Room 138

Bethesda, Maryland 20892

U.S.

301-402-2725 (desk)

301-402-3469 (fax)

Abstract

The National Institutes of Health (NIH) and the research community have been concerned about the increasing periods of training and the rate of entry of new investigators into its pool of funded Principal Investigators (PIs).   Longer periods of training prior to admission to faculty and application for NIH research grant support are reflected in the average age at which investigators receive their first independent research project grant, which has increased from 34.3 to 42.4 over the period from 1970 to 2006. Because sustaining a highly productive research enterprise requires a continuing supply of new investigators, the NIH launched an effort to model the biomedical PI workforce and to estimate the rate of replenishment necessary to stabilize the age of the entire pool. The model also was developed to test policies that may encourage a reduction in the duration of the period training necessary to apply for independent research support. This paper provides an overview of the model developed for this purpose along with initial simulations to address policies being considered.

Key Words:

System dynamics, workforce, simulation, resource planning, STEM

Background

The National Institutes of Health (NIH) and the research community have been concerned for decades about the increasing periods of training and the rate entry of new investigators into its pool of funded Principal Investigators (PIs)[1,2,3,4]. The NIH has used a series of awards and policies to address this issue[5]. For those with research doctorates, longer periods of training leading to award of a doctoral degree and training as a postdoc are reflected in the average age at which investigators receive their first independent research grant, which has increased from 34.3 to 42.4 over the period from 1970 to 2006[5]. The age at which biomedical scientists are hired as assistant professors at U.S. medical schools has increased in a similar fashion[5]. The situation for investigators may have been exacerbated in 2004 when federal funding for biomedical research leveled off after a period of increase during a time of growing scientific opportunity[6]. In the years since 2004 research institutions and medical, biomedical, and clinical researchers have continued to submit applications at a high rate driving success rates down[7]. Over the past few decades, the NIH has seen a profound change in the age demographics of its pool of Principal Investigators (PI's) of NIH research project grants (RPGs) [8,9]. Figure 1 shows the age profile of funded PI's in 1980. The average age was around 39 and there was a distinctive spike in the profile around the ages 36 to 40. Figure 2 shows the age profile of funded PI's in 2005. The

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[1] National Research Council (1994) The Funding of Young Investigators in Biological and Biomedical Sciences, National Academy Press, Washington, D.C.

[2] National Research Council (2005) Bridges to Independence: Fostering the Independence of New Investigators in Biomedical Research, National Academy Press, Washington, D.C.

[3] Garrison, HH, Gerbi, SA, Kincade, PW, (2003) In an era of scientific opportunity, are there opportunities for biomedical scientists? FASEB J. 17: 2169-2173

[4] Xemlo, TR, Garrison, HH, Partridge, NC, Ley, TJ (2000) The Physician-Scientist: Career Issues and Challenges at the Year 2000, FASEB J. 14:221-230

[5] Ruiz Bravo, N. Slide presentation to the Association of American Medical Colleges, 16 June 2006, http://grants.nih.gov/grants/new_investigators/20060619_AAMC_GREAT.ppt

[6] Number of Awards and Award Amounts for NIH Research Grants, Fiscal Years 1999 to 2008; http://report.nih.gov/UploadDocs/T105%202008%20-%20RPG%20-%20Num%20and%20Awd%20Amt%20-%20R1050.xls

[7] Number of NIH Research Project Grant Applications and Awards and Success Rates 1998-2008, see http://www.report.nih.gov/nihdatabook/Charts/SlideGen.aspx?chartId=124&catId=13.

[8] Age Distributions of NIH Research Project Grant Principal Investigators and Medical School Faculty, 1980 – 2006; http://grants.nih.gov/grants/new_investigators/RPG_PIs_AAMCFaculty08252007.ppt#265,1,Slide 1

[9] Research Project Grants include activity codes R00, R01, R03, R15, R21, R22, R23, R29, R33,R34, R35, R36, R37, R55, R56, RL1, RL2, RL5, RL9, P01, P42, PN1, UC1, IC7, U01, U19, U34, DP1, DP2, RCI.

average age shifted to approximately 49 years, and the profile flattened reflecting longer periods of training prior to entering the pool and a higher proportion of PIs at older ages[10].

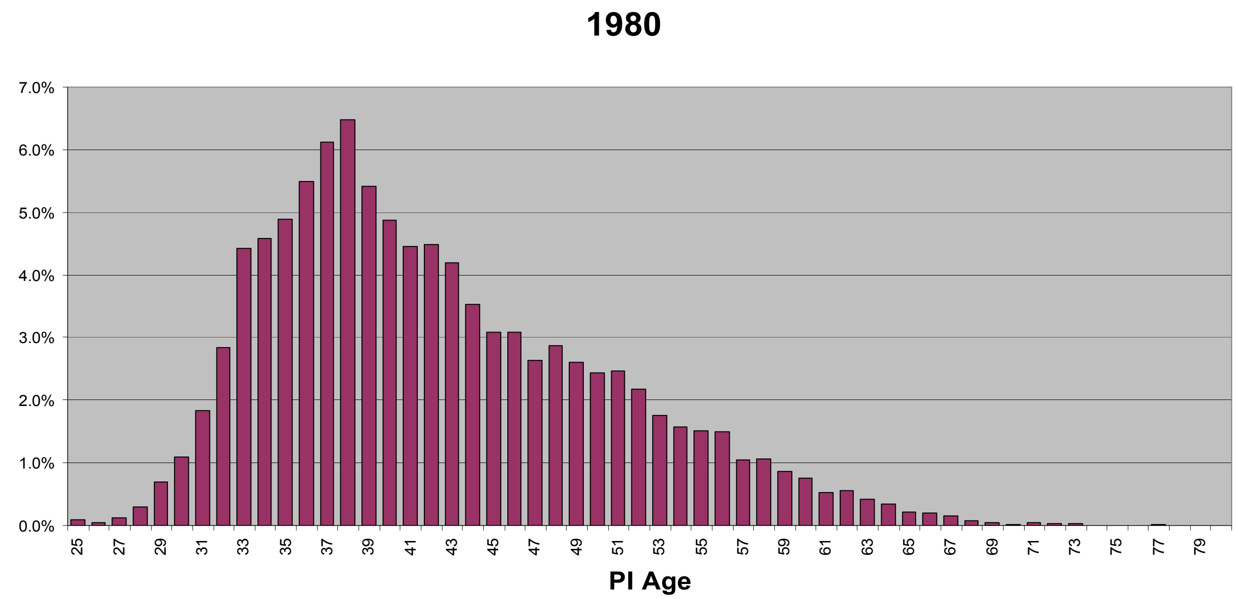

Figure 1: Age Demographic of PI Pool in 1980 (by percent)

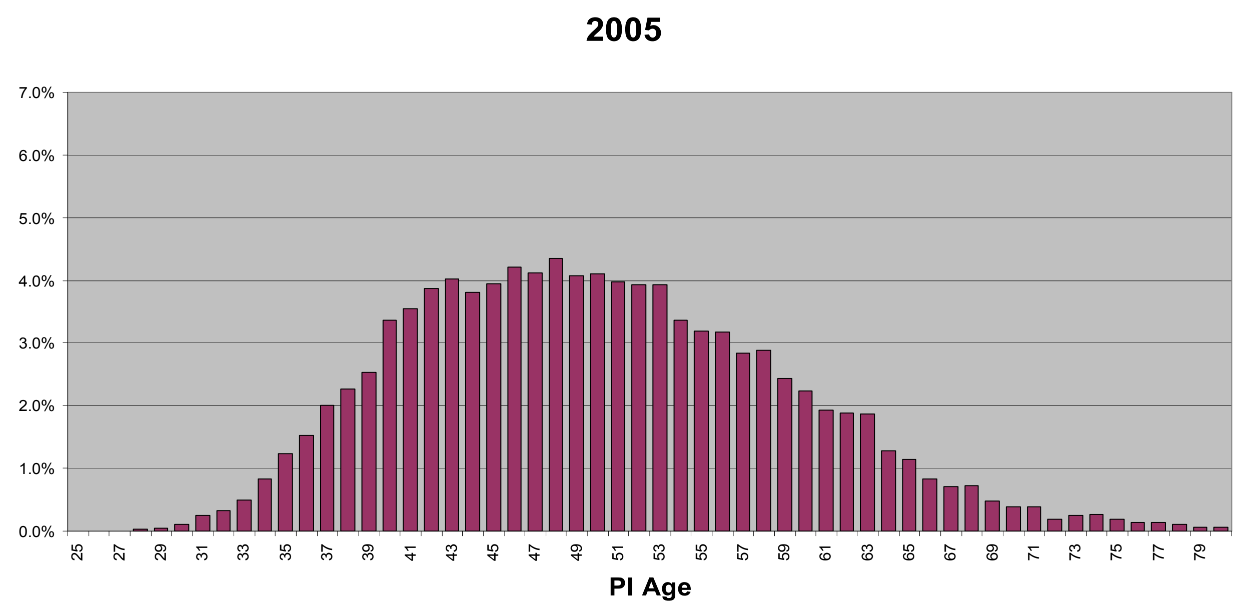

Figure 2: Age Demographic of PI Pool in 2005 (by percent)

[10] Average Age of First Time Investigators – See slide 50 at Education and Employment of Biological and Medical Scientists: Data from National Surveys – Federation of American Societies for Experimental Biology (FASEB) 2008 http://opa.faseb.org/pages/PolicyIssues/training_datappt.htm

To study this situation, the NIH considered the need for a simulation tool to estimate how many new PIs might be necessary to stabilize the age distribution of the entire pool. Such a tool could model the observed changes and provide an objective indicator of how changes in the entry rate of new PIs might affect the average age of the stock PI population. It also could assist with the analysis of policies under consideration to encourage earlier completion of postdoctoral training and transition to research independence. The NIH decided to use systems dynamics (SD) modeling approach[11,12,13,14] as a way to simulate the age –related movement into and out of the PI pool and to test policies to determine their impact on the age distribution of a future PI pool. While the NIH still does not know what the "ideal" age distribution or the "ideal" duration of postdoctoral training it would seem desirable to provide independent support at an earlier age in order to support long and productive careers.

Overview of Workforce Aging Model

The fundamental SD model used for this project is similar to the generic "aging cohort" model that is commonly found in the SD field[13]. This model is based on age as a continuous variable because it is available for approximately 90 percent of all NIH PIs and the age at entry into the pool is roughly related to the duration of training. The use of this variable as the basis for the model is not meant to imply that PIs of any particular age are more productive or desirable than others. To increase accuracy for the purpose of validation, the first model used one year cohort sizes. Figure 3 shows the basic diagram for each cohort model, which we also refer to as an "agent" model.

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[11] Business-Higher Education Forum. www.bhef.com.

[12] Forrester, Jay W. *Industrial Dynamics*, Productivity Press. 1961.

[13] Senge, Peter M. *The Fifth Discipline: The Art & Practice of the Learning Organization*. Doubleday. 1990.

[14] Sterman, John D. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. McGraw-Hill. 2000.

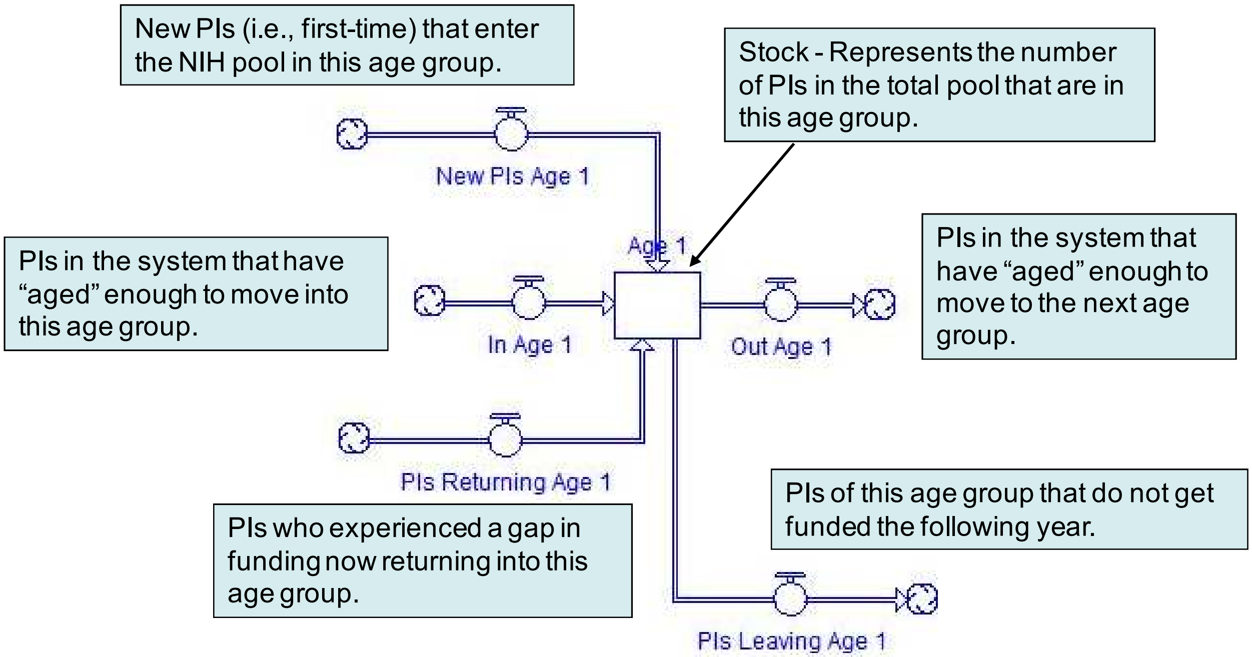

Figure 3: Basic Aging "Agent" Model

In Figure 3, each stock of PI's has three (3) inflows and two (2) outflows. The inflows are the following:

- New PI's of the indicated age who are receiving their first ever NIH grant;
- Returning PI's of that particular age who have received previous grants from NIH but had a period of time in which they were not funded; and
- PI's who are still "in the system" by virtue of continuous funding via a competing or non-competing continuation grant and have aged from the previous age group.

The outflows are the following:

- PI's who are still "in the system" and by virtue of a competing or a non-competing continuation grant are aging into the next funded age group; and
- PI's of that particular age who lost their funding in the indicated year and are now entering a period of being unfunded (perhaps, to return later).

For purposes of clarity, Figure 4 shows the linking of several of these agent models. The full model has 66 agents linked together for ages 25 to 80. Because this is the main part of the model to which new structure may be added later (e.g., feedback loops), the study team[15] affectionately

[15] Workforce Models Study Team: Christine Bachrach, (NICHD); Robin Barr (NIA); Charles Sherman (Dartmouth); Rebecca Clark, (NICHD); Charles Dumais (CSR) Dennis Glanzman (NIMH); Sarah Glavin (NIDCR); Giovanna Guerrero (NINDS); Henry Khachaturian (OD); Israel Lederhendler, (OD); Peter Lyster (NIGMS); Robert F Moore (OD); John Norvell (NIGMS); Judit O'Connor, (OD); James Onken (NIGMS); John Phillips (NIA); Peter Preusch, (NIGMS); Jennifer

called it the "backbone" model. In the end, it is a fairly basic simulation model with complexity only arising from the multitude of simple agents.

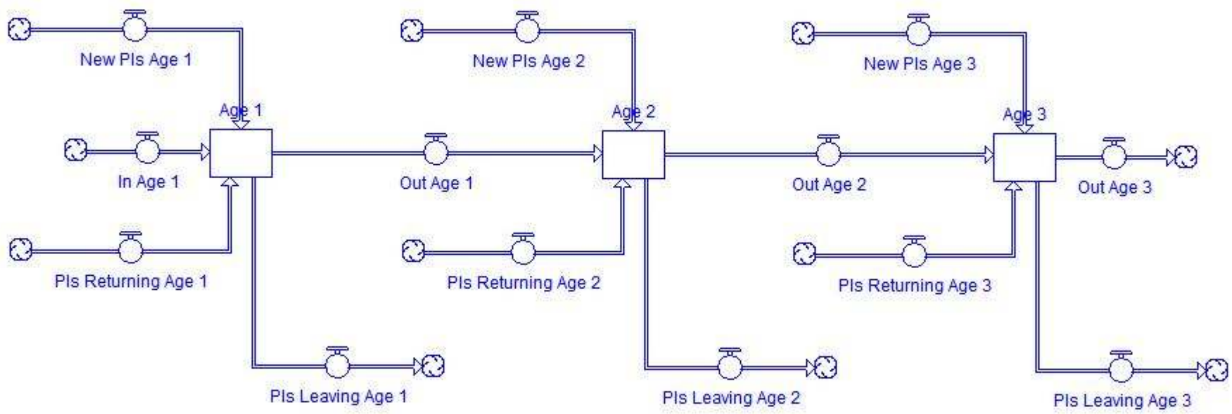

Figure 4: Linking Multiple Age Groups

To make model manipulation easier, the study used a commercially available simulation environment called SimBLOX®[16], which allows the creation of agent models in a drag-and-drop, icon-based interface. Figures 5 and 6 show diagrams of the SimBLOX process and environment. Agent models are represented by icons, which are called SimBRIX[15] in the SimBLOX environment. The user drags, drops, and connects SimBRIX to form higher level models. In this workforce aging model, each icon represents an age cohort. Arrow connectors represent the aging process from one group to the next older group.

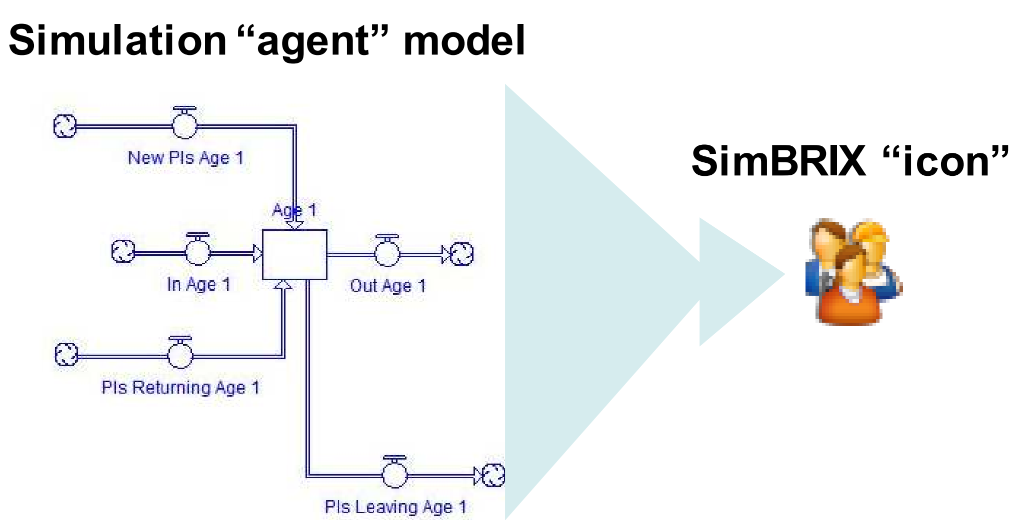

Figure 5: Agent Models Converted to SimBRIX Icons in SimBLOX Interface

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Sutton (OD); Richard Suzman (NIA); Neil Thakur(OD) [E]

[16] See http://viasimcorp.com/products.html

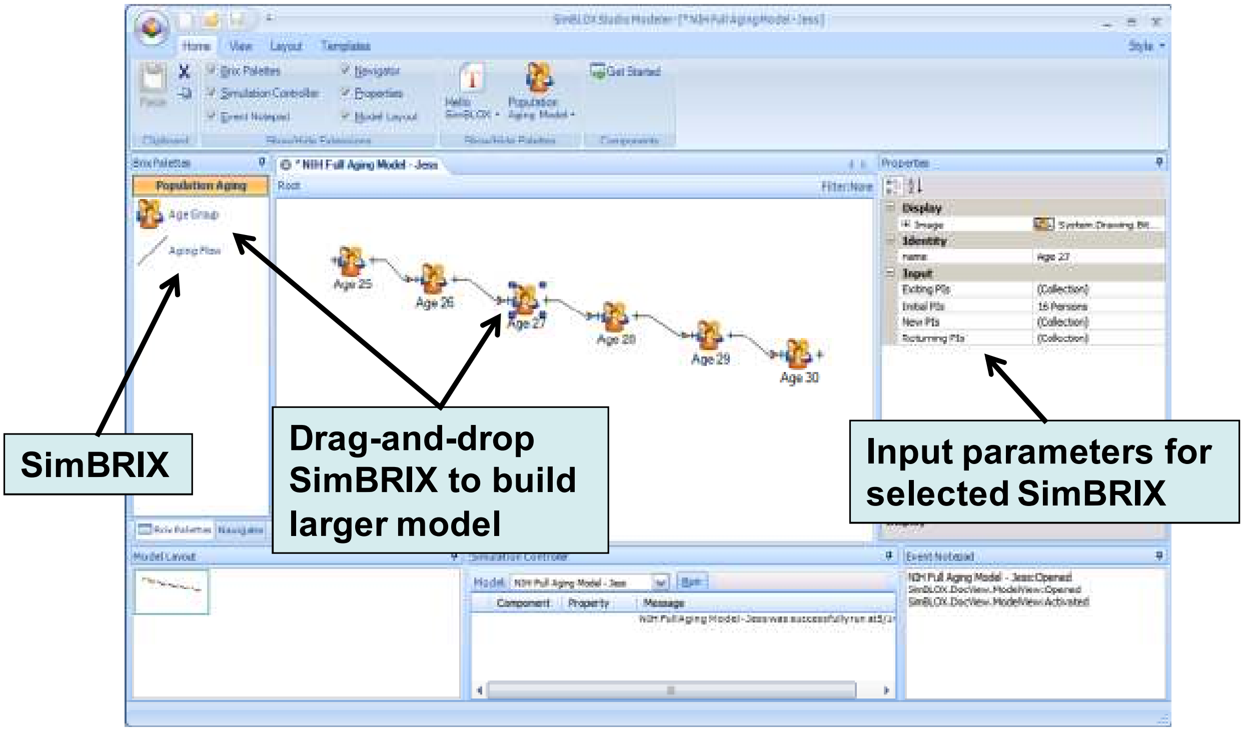

Figure 6: SimBLOX Interface with Age Group SimBRIX

Model Validation

Historical age-related rates of influx of new and returning investigators along with age-related rates efflux of those leaving were used to populate the SimBLOX model[17]. At that point the assembled model was loaded with stock values for NIH RPG PIs for each age group observed in FY1980 and the model generated simulated population values for each year between 1981 and 2006. Figure 7 shows a small segment of the entire simulation and highlights discrepancies between the actual NIH historical data on PI stock values and the age-related values calculated by the simulation after allowing the simulation to run for 26 years. A zero indicates that the simulation results exactly matched the historical data on the entire population of PIs. Discrepancies between actual and simulated values "cascade" diagonally from upper left to lower right through the chart indicating how numerical data discrepancies in a particular year are propagated in the simulation. These small discrepancies in stock values compared to historical influx and efflux rates helped validate the operation of the simulation and the model structure.

Picking a single fiscal year in Figure 8 shows the age distribution for FY2005 for both historical NIH data and simulation results based on historical annual rates of influx and efflux using stock

[17] Relevant data on the RPG pool along with influx and efflux rates can be found at http://grants.nih.gov/grants/new_investigators/nih_age_data_principal_investigators_1970-2006.xls Note that these data include all Research Project Grants (RPGs)[9] for PIs who have known birth dates.

values from 1980 alone. The RMS value for these data sets is 0.38% (0.0038)[18], indicating a tight fit between historical data and simulation results even after 25 years. This should not be surprising given the simplicity of the SD model and the accuracy of reports on the stock population and the relevant flow values. The NIH study team wanted the model to offer a high level of confidence in the SD modeling approach before investing additional time and effort into adding appropriate feedback loops, etc. The novel SD methodology offered a much higher level of confidence than previous statistical trends and parametric fit models. .

Time/Units:	FY80	FY81	FY82	FY83	FY84	FY85	FY86	FY87	FY88	FY89	FY90	FY91	FY92	FY93	FY94	FY95	FY96	F
Age 25	0	2	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	
Age 26	0	0	2	1	0	0	0	0	1	0	0	0	0	0	0	1	0	
Age 27	0	4	0	2	3	0	-1	-3	5	-3	0	-3	-3	-3	1	2	3	
Age 28	0	0	4	0	1	4	1	2	-1	4	1	0	2	-1	-1	-2	-1	
Age 29	0	0	0	4	0	1	4	1	2	-1	4	1	0	2	-1	-1	-2	
Age 30	0	0	0	0	4	0	1	4	1	2	-1	4	1	0	2	-1	-1	
Age 31	0	0	0	0	0	4	0	1	4	1	2	-1	4	1	0	2	-1	
Age 32	0	0	0	0	0	0	4	0	1	4	1	2	-1	4	1	0	2	
Age 33	0	0	0	0	0	0	0	4	0	1	4	1	2	-1	4	1	0	
Age 34	0	0	0	0	0	0	0	0	4	0	1	4	1	2	-1	4	1	
Age 35	0	0	0	0	0	0	0	0	0	4	0	1	4	1	2	-1	4	
Age 36	0	0	0	0	0	0	0	0	0	0	4	0	1	4	1	2	-1	
Age 37	0	0	0	0	0	0	0	0	0	0	0	4	0	1	4	1	2	
Age 38	0	0	0	0	0	0	0	0	0	0	0	0	4	0	1	4	1	
Age 39	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	1	4	
Age 40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	1	
Age 41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	
Age 42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	

Figure 7: Discrepancies Between Historical Data and Simulation Results

[18] Root Mean Square Error calculation as described at http://en.wikipedia.org/wiki/Mean_squared_error

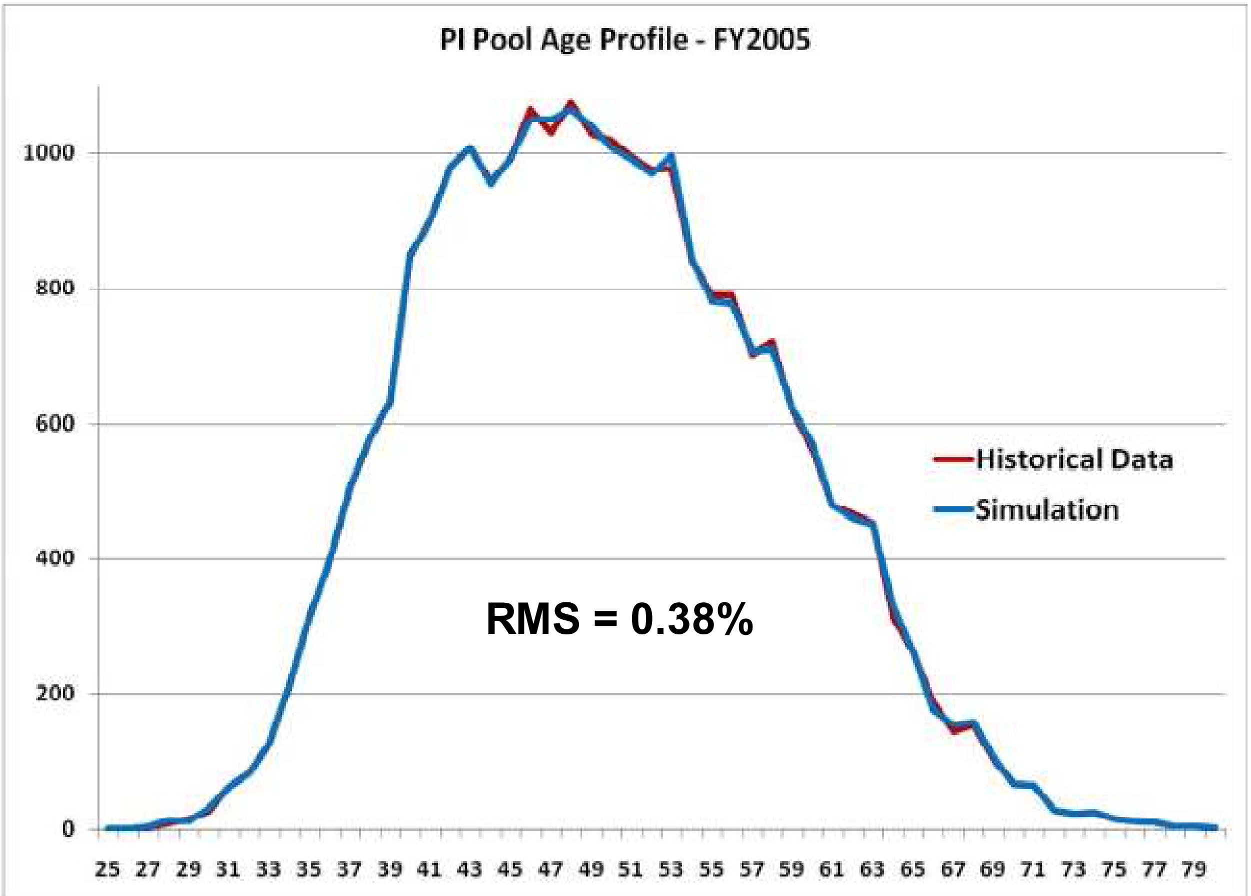

Figure 8: Age Profile for FY2005 of Historical NIH Data and Simulation Results

Using influx and efflux rates from FY2005, the same simulation model was extended until FY 2015, as shown in Figure 9, or up to ten years past the last reliable data set (FY 2006)[16]. The lighter gray and thinner lines represent the earlier years of the simulation results. For later years, thicker and darker lines suggest an `age profile that continues to flatten and stretch to the right. For FY2015 in the simulation, the average age is 52.1 years old. While the results in Figure 10 do not account for changes in budget, award amounts, award duration, or the age of the applicant pool; the perpetuation of the aging suggests a reduced proportion of investigators younger than age 40 and a growing proportion of investigators above age 65.

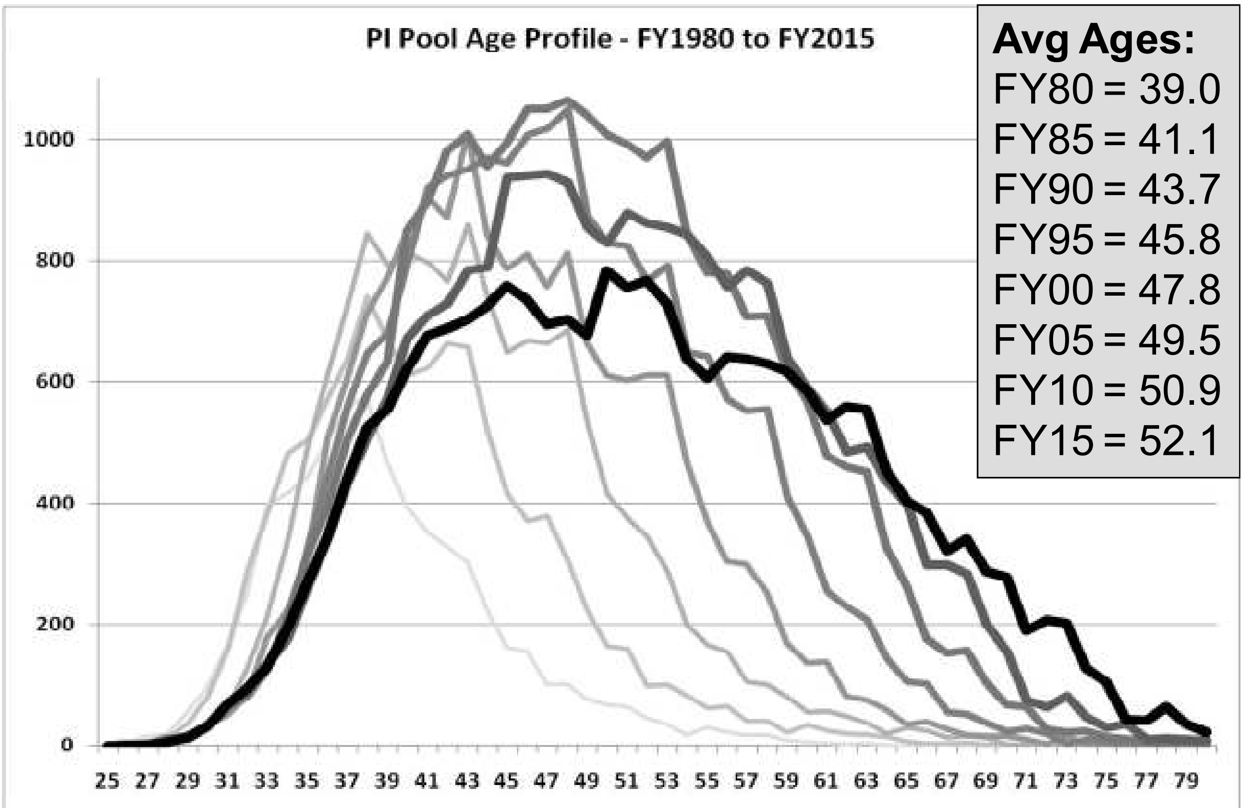

Figure 9: Age Profiles of Simulation Results for All Years of the Simulation

Policy Testing Results

After demonstrating the validity of the SD approach and the basic "backbone" model, the study team decided to use the basic model to test the potential impact of accelerating the flow of new investigators into the PI pool and the effects of policies that might reduce the age of entering PIs by encouraging applications at an earlier point in the investigator's career. The objective in the simulation was to determine how many new investigators in various scenarios would be needed to keep the average age of the PI pool approximately constant. Although the model did not incorporate the effects of exogenous variables such as budgetary changes, there was sufficient confidence to test these simple hypotheses.

Because the model has no formal feedback loops to account for exogenous variables, the study team developed a few high-level assumptions to capture the influence of basic feedback concepts. For example, in a constant budgetary environment it was assumed that the number of research projects and therefore the number of PI's would remain relatively constant. If the total number of PI's remained constant, the net difference among new, returning, and exiting PI's would be zero. As the number of new PI's entering the system increased (or decreased) in the simulation, the number of returning PI's and exiting PI's were adjusted accordingly so that the net effect on the total population was zero. The age distribution of the population of both entering and exiting PIs were maintained in these simulations.

For this part of the study, the cohort size was also changed from a single year to five (5) years to simplify and decrease data inputs. The model using five year cohorts was validated as described for the model with single year cohorts. Figure 10 shows one of the spreadsheet input forms used for the SimBLOX model. Based on NIH data for FY 2006, the full complement of PIs (2,100) entering was distributed around age 41. This Baseline Scenario involved 2,100 new PI's entering the system each year, approximating FY 2006 new investigator flux rates[17]. The basic age distribution was retained but distributed over 1,600, 2,600, and 3,100 PIs in order to test the effects of adding more or fewer PIs to the system. The change in input of new PIs was then balanced by increasing or decreasing the number of exiting PIs using the observed age distribution of those that exited or returned to the stock pool.

	Total New PIs:	2100
	Distribution	Sim Inputs
INPUTS: New PI's		
26-30	2.0%	42.0
31-35	14.0%	294.0
36-40	30.0%	630.0
41-45	26.0%	546.0
46-50	13.0%	273.0
51-55	8.0%	168.0
56-60	4.0%	84.0
61-65	2.0%	42.0
66-70	1.0%	21.0
71-75	0.0%	0.0
76-80	0.0%	0.0
Total	100.0%	2100

Figure 10: Baseline Scenario Inputs for New PI's

The total number of funded PIs in this simulation was held constant using the historical age distributions to balance input with exit rates. Similar simulations were carried out assuming that policy changes could reduce the age distribution of entering PIs.

A total of twelve (12) simulations were run using four (4) different values for the number of new PI's entering the system and three (3) different scenarios for the age distribution percentages.

- Baseline Scenario: Age distribution of new PI's is as shown in Figure 11, with an average age of approximately 41 years old (based on historical NIH data).
- ESI Scenario 1: Age distribution of new PI's is preserved but the observed age distribution was shifted to younger ages so that average age of new PI's is 35.
- ESI Scenario 2: Age distribution of new PI's is preserved but the observed age distribution was shifted to younger ages so that average age of new PI's is 38.

Early Stage Investigator (ESI) Scenarios 1 and 2 where conducted to simulate a policy that has since been implemented[19]. The ESI policies focused on enriching the pool of entering PIs with those who have had shorter periods of training as reflected in a lower average age. The simulations were constructed to show how enrichment of the pool in ESIs would affect the number of New Investigators needed to maintain a constant average age of the entire PI pool. Figure 11 shows the results of the 12 simulation runs for the years 2011 and 2016 for the overall average age of the pool of funded PI's. The simulations initialized with 2006 data, so the results in Figure 11 represent five years out and ten years out.

Average Age of PI Pool in 2011

Number of New PIs in Scenario	Baseline Scenario Average Age 42	ESI Scenario 1 Average Age 35	ESI Scenario 2 Average Age 38
1,600	51.8	49.3	50.3
2,100	51.0	47.7	49.0
2,600	50.2	46.2	47.8
3,100	49.4	44.6	46.5

Average Age of PI Pool in 2016

Number of New PIs in Scenario	Baseline Scenario Average Age 42	ESI Scenario 1 Average Age 35	ESI Scenario 2 Average Age 38
1,600	54.2	49.2	51.2
2,100	52.5	46.0	48.6
2,600	50.9	42.9	46.1
3,100	49.3	40.0	43.6

Figure 11: Simulation Results for Multiple Policies for New PI's

The status quo is approximately equivalent to the Baseline Scenario using 2,100 new PI's. This number is approximately equal to the historical influx of new investigators[17]. Thus, the simulation suggests that "doing nothing" will lead to an increased average PI age from 49.4 years in 2006 to about 51.0 in 2011 and 52.5 in 2016. This change in the average pool age is similar to historical trends[8]. In all cases, the pool age changes in predictable ways again validating the overall structure of the model.

The age profiles of the resulting stock PI pool vary according to the scenario tested and the entry rate of new PIs. For example, Figure 12 shows the age profile for the Baseline Scenario adding

[19] Encouraging Early Transition to Research Independence: Modifying the NIH New Investigator Policy to Identify Early Stage Investigators, September 26, 2008; http://grants.nih.gov/grants/guide/notice-files/NOT-OD-08-121.html

1,600 new PI's each year. Notice that the trend of the "flattening" profile would be accelerated by reducing the proportion of PIs at entry and increasing the proportion of PIs at older ages. Figure 13 shows the age profile results for the Baseline Scenario with 3,100 new PI's each year. This proved to be an interesting policy because it maintained the average of the PI pool at about 49.4 and a similar age profile over the 10 year simulation period. Notice that the age profile shifts slightly to the left (i.e., younger), but still stays approximately the same.

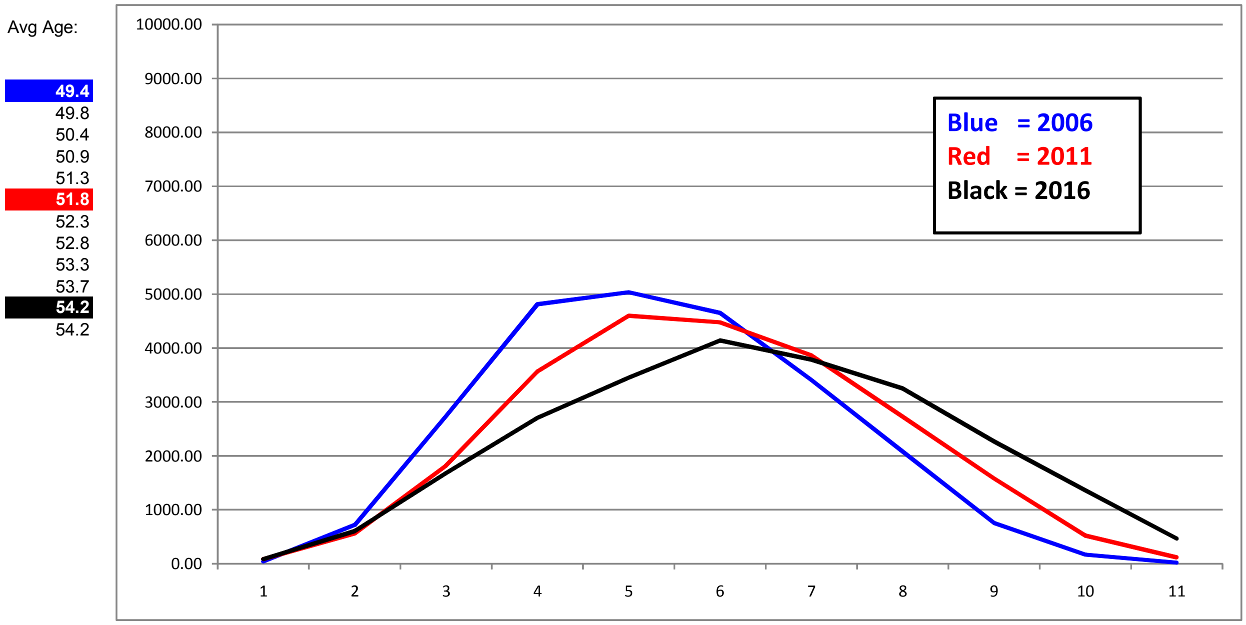

Figure 12: Age Profiles of Simulation Results for 1600 New PI's for Baseline Scenario

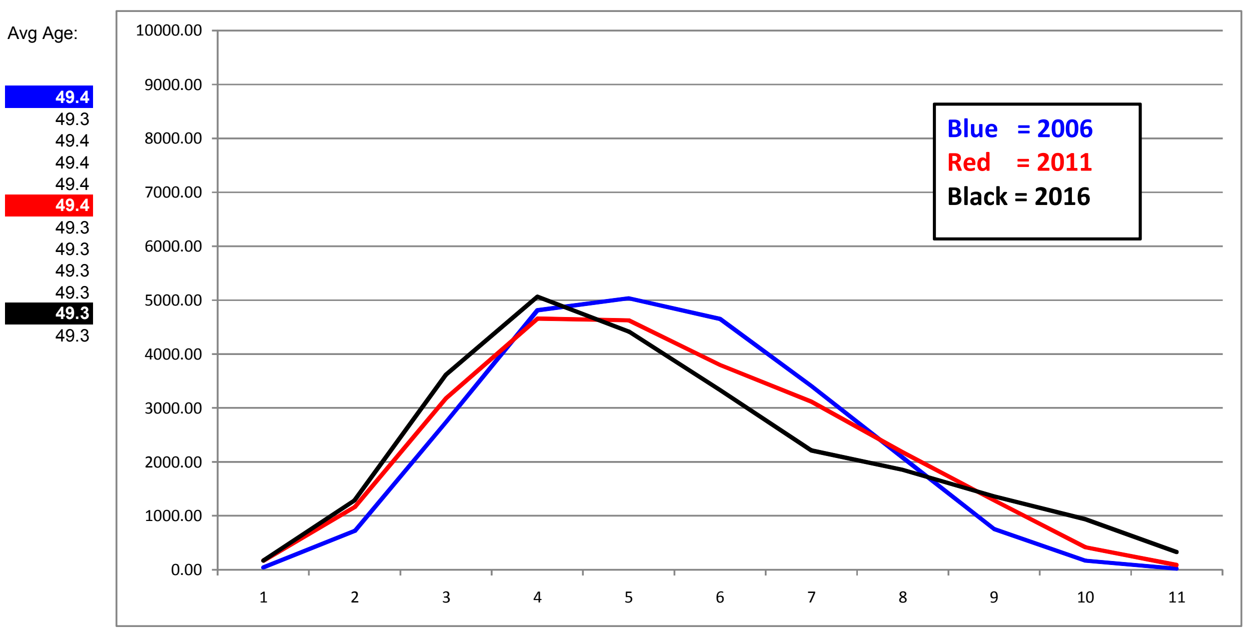

Figure 13: Age Profiles of Simulation Results for 3100 New PI's for Baseline Scenario

Figure 14 shows an example of age profiles of one of the other policies: ESI Scenario 2 (average age of new PI's is 38) with 3,100 new PI's. There was a dramatic shift in the age profile from 2006 to 2016 presumably because the number of new PIs over the age range of 50 to 60 is lower than those who leave. This simulation demonstrates that the use of aggressive New Investigator and ESI policies could change the age of the PI pool but could result in substantial changes in the overall age distribution of the pool. Such changes may or may not be desirable.

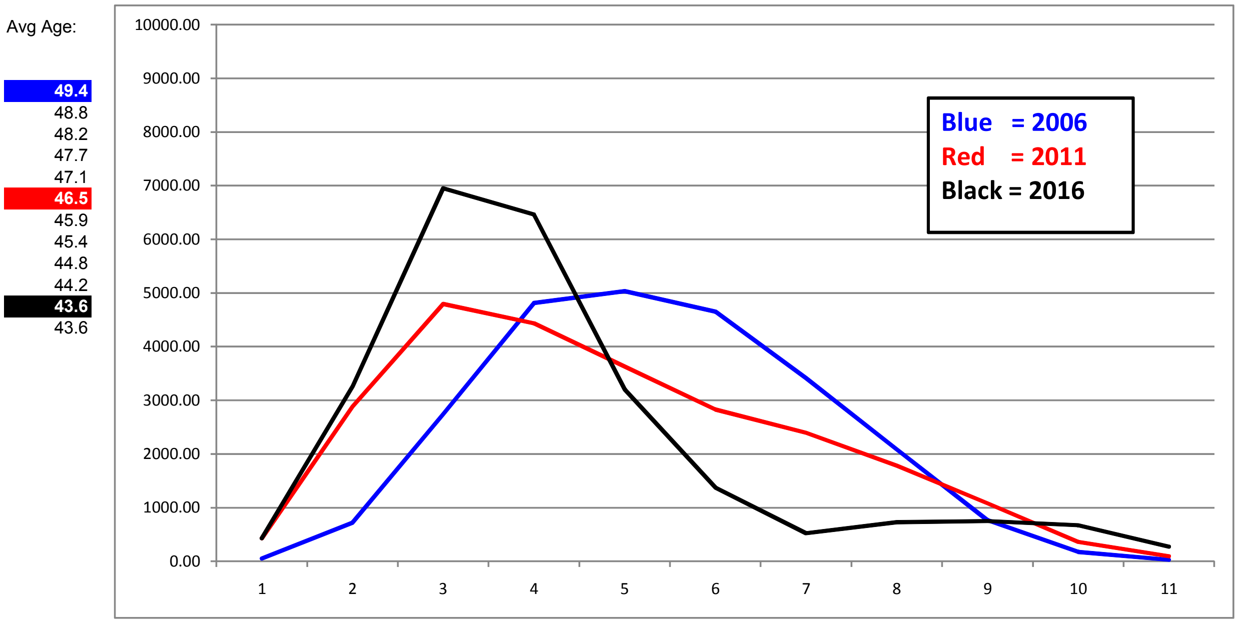

Figure 14: Age Profiles of Simulation Results for 3100 New PI's for ESI Scenario 2

Conclusions and Next Steps

A simple system dynamics workforce model, as presented here, can be extremely powerful as a means of guiding policy decisions. In some ways simple models are better than more advanced models because they incorporate relatively few assumptions and are easy to explain. On the other hand the absence of feedback loops limits an assessment of mitigating effects of limits on number of applicants or changes in budgetary policies that might have profound effects on the age distribution of this population. For example, feedback loops might describe practical limitations in the supply of new investigators and the effect of awarding grants to a larger proportion of first-time applicants. But, the absence of guiding data would require the introduction of complex and potentially risky assumptions to adjust for those parameters. An unfettered but structurally sound model permits exploration of scenarios that may not be practical, but nevertheless can be useful in considering the implications of policy changes.

In this specific case, the model helped NIH understand that the current rate at which New Investigators enter the RPG PI pool (2,138 in FY 2006)[17] is inadequate to maintain the average age of the stock pool of PIs. It also indicates that nearly 3,100 new RPG investigators would be required to balance the age. Although the NIH receives a sufficient number of applications from new investigators increasing the number of applications receiving awards by nearly 50% would require selecting applications across a much wider range of merit scores. In the absence of an assessment of the importance of maintaining stability in the age distribution of the overall PI pool, substantial increases in the number of New Investigators may not be practical.

Another finding relates to the average age of entering investigators. Until recently, the average age at entry into faculty positions and the average age at receipt of the first NIH research grant have increased steadily for several decades[10]. The observed changes in age at entry are thought to reflect longer periods of training at the postdoc level. Therefore, methods to encourage early entry into the PI pool might be desirable. Accordingly the NIH developed and implemented the Early Stage Investigator (ESI) policy that provides adjustable incentives in review and funding of applications from New Investigators who are within 10 years of completing their terminal degree or medical residency[19]. It is possible that such policies will, over time, reduce the average age of the pool of new investigators by encouraging grantee institutions to hire faculty after a shorter period of postdoctoral training and by encouraging applicants to develop and submit grant applications at an earlier point in their careers. The simulations offered here are only approximate descriptions of the changes in the age of entering PIs that may result from the ESI policies, but these efforts indicate that the effects of the ESI policy and other changes can be effectively modeled.

This kind of model permits the testing of policy options in ways that are not possible with statistical models. The development of such models reveal interesting relationships between those who enter and those who exit the stock pool and will eventually permit simulation of an expanding or contracting pool of PIs. It also may be possible to enhance the model to include information about the application and awards related to PIs in order to better predict workloads and other operational factors. Finally, it may be possible to incorporate variables and feed-back loops that permit modeling of changes in the NIH budget to allow simulation of the impact of large changes in funding such as those associated with the American Recovery and Reinvestment Act of 2009[20].

The development of models of this type could be extended to any STEM workforce or any other workforce for that matter. In all cases, such models are dependent on the ongoing and reliable collection of information on aspirants and members of the pool. It goes without saying that any modeling effort will be limited by practical considerations. In this regard, there is no information on the most desirable age profile for NIH supported PIs although it stands to reason that earlier advancement to independence as a researcher will permit longer and more productive careers. Although such tools are valuable in the development of policies and can help identify the eventual outcomes, policy makers must continue to adhere to fundamental principles. For the

[20] Grant funding Opportunities Supported by the American Recovery and Reinvestment Act of 2009 (ARRA); http://grants.nih.gov/recovery/

NIH that means continuing efforts to nurture the careers of individual investigators and to identify and fund the most meritorious biomedical research[21, 22].

[21] The authors wish to thank members of the study team[15] for guidance during the course of this study. We also wish to thank Mr. John Bartrum and Drs. Elias Zerhouni and Norka Ruiz Bravo for recognizing the importance of this approach.

[22] This study was conducted by the ViaSim Corporation under NIH contract number HHSN27600700250U with funds derived from NIH Evaluation Setaside Award