A Dynamical-Systems Approach to Policy Analysis

Weiqiu Yu

Department of Economics
University of New Brunswick

Preliminary Draft
October 2008

Abstract

In a complex system where many factors interact with each other over time, how does the system change in response to a change in certain policy variables? More importantly, is it possible to change policy variables to achieve system optimality and stability? This paper addresses these issues with a dynamic systems approach via a simple example of three system variables and several policy interventions. It also attempts to apply the approach to an analytical framework for human capital development and policy developed by Ruggeri and Yu (2000).

Key Words: Dynamic Systems, Feedback Loops, Policy Analysis, Human Capital

---

Prepared for presentation at the 36th annual conference of the Atlantic Canada Economics Association, Acadia University, October 24-26, 2008

Introduction

Little theoretical work exists that proposes general mechanisms for how public policies may influence certain economic variables such as human capital formation. Dynamic systems approach is an analytical technique for the computational modeling of complex systems in order to understand the ways that the system functions and how the system corresponds to changes in certain control variables such as public policies over time.

A system may be defined as a collection of interacting variables that function together towards a specific goal. Within a typical system, there are variables that can be controlled for (such as public polices) and variables that serve as objectives including child development, economic growth, and employment. For example, a province like New Brunswick can be viewed as a system whose purpose is to provide employment, essential services, and other social benefits for its inhabitants by conducting proper public policies.

The dynamic systems approach is not a new idea. Emerging from the field of biology, and engineering after World War II (Levin & Fitzgerald, 1992), the approach has been used in social science research (Hanneman & Patrick, 1997), though not as widely as in other fields such as engineering (e.g., Cao, Bennett & Zhang, 2000) and operations research (e.t., Zulch Rinn, & Strate, 2001). The approach has also been applied to other areas such as child development (Yoshikawa and Hsueh, 2001) and criminal justice (Auerhahn, 2008).

This paper argues that dynamic systems models can be very useful to economists for public policy research. They can be used in a variety of ways—to gain greater insight into processes of system change, to track the development of specific system variables, and to estimate projected system growth. They can also be used to conduct analysis with a variety of policy scenarios—making them useful tools for theoretical development and policy evaluation, as well as more pragmatic considerations such as program, facilities, and overall system planning (Auerhahn, 2008). In this paper, using a highly simplified model, I show what is involved in this approach and how it works for developing and integrating public policies and program initiatives.

The Model

Consider a complex system where many factors interact with each other over time. The questions is, how does the system change in response to a change in certain policy variables? More importantly, is it possible to change policy variables to achieve system optimality and stability? This section attempts to answer this question by first introducing some components of the model and then by illustrating an example.

1. *Relationships*

Consider two system variables A and B. Further, assume A has an effect on B [B =

f(A)]. In notation form, we can present this as an arc from $A \longrightarrow B$ indicating that A has an impact on B. We can build on this to include the direction of effect. For example, $A \xrightarrow{+} B$ indicates that A has a positive impact on B while $A \xrightarrow{-} B$ indicates that A has a negative impact on B.

2. *Feedback Circles*

Now suppose we have three inter-related factors A, B and C shown in Figure 1.

Figure 1: A three-variable system

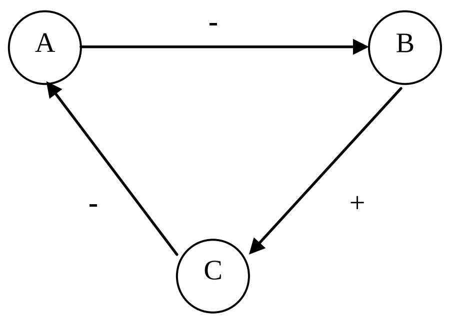


Figure 1 shows that: A has negative influence on B; B has positive influence on C; and C has negative influence on A. The existence of direct influence from factor C and indirect influence from factor B is called a feedback circle. Such circles can be positive or negative feedback circles. In this example, we have a positive feedback circle because the total number of negative arcs is 2. To determine the sign of the feedback circle, let n be the number of negative arcs in the circle. Thus, the feedback circle is positive if $(-1)^n = 1$ and negative if $(-1)^n = -1$.

3. *Strength of Influence*

If factor A influences factor B, and the influence can be shown by a mathematical model, i.e. B = f(A), then when the value of A is given, the value of B can be calculated mathematically. However in most cases, it is very difficult to accurately interpret the relationship between A and B by using a mathematical model. In the absence of a model, an indicator variable is chosen to measure the strength of an influence as follows:

Table 1: Strength of influences

Indicator Variable	Strength of Influence
0	No influence between factors, the arc can be omitted
1	Very weak influence between factors
2	Weak influence between factors
3	Medium influence between factors
4	Strong influence between factors
5	Very strong influence between factors

The value of an indicator is often determined by existing studies in a given field. For example, given the relationship between quantity of gasoline demanded (factor B) and the price of gasoline (factor A), the law of demand states that all else equal, an increase in A leads to a decrease in B. The relationship between A and B can be estimated using observations on these variables.

4. *Matrix of Factor influences*

Consider three factors A, B, and C interacting with each other and represented in the following matrix of factor influences:

Table 2: Matrix of factor influences

		Outcome Indicators		
Influence		A	B	C
	A	aa	ab	ac
	B	ba	bb	bc
	C	ca	cb	cc

The parameter in each cell of the above matrix (e.g., aa, ab, etc.) indicates the direction and strength of the influence between two factors. The rows are the influence variables, while the columns identify the outcomes from changes to the influence variables. For example, if ab = –2, it means that A has a negative influence on B and the influence is weak as defined in Table 1.

5. *Change over time*

Consider factor A, where X_t denotes the value of A at the time t. Let P_{At} be the aggregate influence of all factors including policies within the system on A during the period t to t+Δt. The value of A at time t+Δt can be written as: $X_{t+\Delta t} = X_t^{PAt}$. Similarly, if we let Y and Z represent the quantities of B and C, their values at time t+Δt can be written as: $Y_{t+\Delta t} = Y_t^{PBt}$ and $Z_{t+\Delta t} = Z_t^{PCt}$ respectively where P_{Bt} and P_{Ct} are the aggregate influence of all factors on B and C: The following example further illustrates these concepts and parameter definitions.

An Example

Consider a simple ecological system within which there is:

1) 100 square kilometer meadow with,

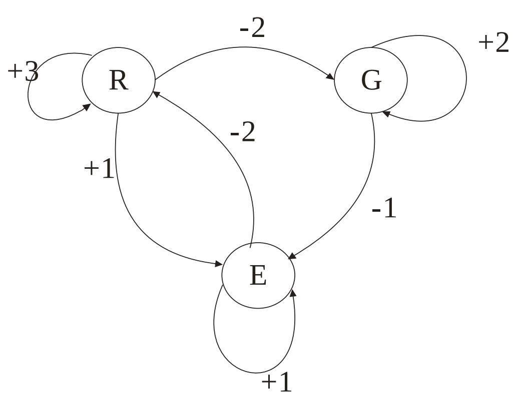
2) G amount of grass that feeds,

3) R number of rabbits, and

4) E amount of eagles.

And the system is depicted by the following feedback circles (Figure 2).

Figure 2: Feedback Circles without Intervention



The feedback loops show how these three variables are interrelated with the strength of influence summarized in the following matrix (Table 3).

Table 3: Matrix of Factor Influence without Intervention

Influence Factors	Outcome Indicators: R	G	E
R	+3	-2	+1
G	0	+2	-1
E	-2	0	+1

Note that the information determining the feedback circles and the strength of influence usually comes from either well-establish theories, or empirical observations (data), or by assumptions. For example, the number "+3" in the first row could come from a theory or a rabbit expert suggesting that rabbits multiply by three times during each period. The value of "0" in the second row assumes that there is plenty of grass for rabbits over the entire study period thus any changes in G will not change R. The number "-1" in row 2 shows that more G will have a slight negative impact on E according to experts since more (thus dense grass) helps rabbits to hide thereby making it more difficult for eagles to capture them.

Next, since these variables are measured in different physical units, it is desirable to convert them into "unit free" measures for easy manipulation of the model. To this end, we must specify or estimate the maximum (or target) values for each variable. Of course, at any given point of time (t=0), we can find the current values of these variables. Table 4 presents the current, maximum and relative values of these variables where: relative value = current value / maximum value.

Table 4: Variables values in the System

	Current Value	Max. Value	Relative Value
R	60 hares	100 hares	0.6
G	7 kg	10kg	0.7
E	20 eagles	50 eagles	0.4

Let R_t, G_t, and E_t be the relative values of R, G, and E respectively at time t. Table 4 shows that at time t = 0, R_0 = 0.6; G_0 = 0.7; E_0 = 0.4. Further, let $P_{Rt,}$ P_{Gt} P_{Et} be the aggregate influence of all factors on R, G, and E respectively at time t, defined as follows:

P_{Rt} = [1+(negative impact index on R)]/[1+(positive impact index on R)]

= (1+2*E_t) / (1+3* R_t),

P_{Gt} = [1+(negative impact index on G)]/[1+(positive impact index on G)]

= (1+2*R_t) / (1+ 2*G_t), and

P_{Et} = [1+(negative impact index on E)]/[1+(positive impact index on E)]

= (1+*G_t) / (1+ R_t + E_t)

Thus, when t =1:

P_{R1} = (1+2*0.4) / (1+3*0.6) = 0.642857.

$$R_1 = R_0^{PR1} = 0.720083$$
$$P_{G1} = (1+2*0.6)/(1+2*0.7) = 0.91666$$
$$G_1 = G_0^{PR1} = 0.721118$$
$$P_{E1} = (1+1*0.7)/(1+1*0.6+1*0.4) = 0.85$$
$$E_1 = E_0^{PR1} = 0.458934$$

When t = 2:

P_{R2} = (1+2*0.458934) / (1+3*0.720083) = 0.606872

$$R_2 = R_1^{PR1} = 0.819312$$
$$P_{G2} = (1+2*0.721183)/(1+2*0.721118) = 0.9999152$$
$$G_2 = G_1^{PR2} = 0.721318$$
$$P_{E1} = (1+1*0.721118)/(1+1*0.720083+1*0.458934) = 0.5405443$$

Continuing the recursive calculations for t =3, 4, 5, 6, 7, 8, 9, 10, the values for R_t, G_t, and E_t for the first 10 years are presented in Table 5.

Table 5: Values for R_t, G_t, and E_t , when t = 0 to 10

t	***Rt***	***Gt***	***Et***
1	0.720083	0.721118	0.458934
2	0.819312	0.721318	0.5405443
3	0.886975	0.702657	0.638443
4	0.928119	0.665664	0.738944
5	0.952331	0.60738	0.827835
6	0.966929	0.520005	0.896517
7	0.976208	0.390458	0.943662
8	0.982458	0.210334	0.972764
9	0.986881	0.038629	0.988754
10	0.990121	0.000001	0.99606

Table 5 shows that without any intervention, the number of rabbits and eagles will increase while the amount of grass will decrease over time. Furthermore, going from time period 8 to time period 9, there is a dramatic decrease in the amount of grass. In period 10, there is hardly any grass left. Without grass, there will be no rabbits; without rabbits, there will be no eagles. Thus, we conclude that without any intervention, this system will begin to collapse in period 8. To prevent this from happening, let us now consider the following policy interventions.

Policy I

Assume the first intervention is to allow people to kill rabbits, and eagles. The system now has 4 variables: R, G, E, and P where P represents number of people within the system. This policy is implemented in time period 8, prior to the collapse of G. Further, let the relative value for P be 0.4 in period 8, following the same procedure as in the previous section, we calculate the relative values of all four variables in Table 6 along with their corresponding influence indicators.

Table 6 shows that from year 8 to year 20, the amount of grass would eventually increase but the rabbit population would be wiped out completely in period 18. Thus, it is evident that ecological damage will occur and the policy must be adjusted.

Table 6: Values for R_t, G_t, E_t , and P_t when t = 8 to 20 with Policy I

t	*Rt*	*Gt*	*Et*	*Pt*	P_{Rt}	P_{Gt}	P_{Et}	P_{Pt}
8	0.982459	0.210334	0.972764	0.400000	1.151531	1.142382	0.409558	0.298043
9	0.979828	0.168463	0.988754	0.761021	1.528524	1.249594	0.393610	0.268125
10	0.969331	0.108005	0.995558	0.929393	1.716658	1.293181	0.373709	0.256787
11	0.947933	0.056243	0.998338	0.981373	1.800866	1.293847	0.358502	0.254606
12	0.908196	0.024142	0.999404	0.995224	1.873954	1.271044	0.352229	0.256225
13	0.834892	0.008799	0.999790	0.998774	1.995812	1.223024	0.355877	0.260861
14	0.697572	0.003062	0.999925	0.999680	2.262921	1.131664	0.371849	0.270477
15	0.442644	0.001429	0.999972	0.999913	3.006790	0.961751	0.409982	0.290484
16	0.086250	0.001836	0.999989	0.999975	5.560974	0.724164	0.480211	0.324022
17	0.000001	0.010436	0.999995	0.999992	6.999931	0.666667	0.505219	0.333335
18	0.000000	0.047757	0.999997	0.999997	6.999984	0.666667	0.523879	0.333334
19	0.000000	0.131631	0.999999	0.999999	6.999993	0.666667	0.565816	0.333334
20	0.000000	0.258764	0.999999	1.000000	6.999997	0.666667	0.629382	0.333333

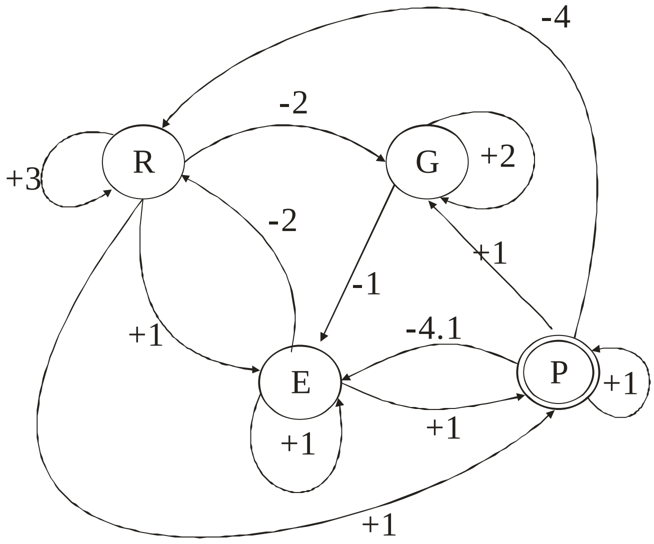
Policy II

Consider the following set of policy interventions:

1. Issue licenses to allow people to kill rabbits and shoot eagles;
2. Put charges on killing and shooting activities, and use these charges toward grass maintenance; and
3. Control the number of licenses.

The system with Policy II is shown in Figure 3 where the additional feedback circles show how P interacts with R, G, and E under Policy II.

Figure 3: Feedback Circles with Policy II



The new matrix of factor influences with Policy II is presented in Table 7.

Table 7: Matrix of Influence with Policy II

	R	**G**	**E**	**P**
R	+3	-2	+1	+1
G	0	+2	-1	0
E	-2	0	+1	+1
P	-4	1	-4.1	+1

The results for R_t, G_t, E_t , and P_t from t = 8 to 30 with Policy II are presented Table 8 and graphed in Figure 4.

These results show that from period 8 to 30, the system variables would be relatively stable with Policy II. Thus, we conclude that Policy II would achieve system stability up to the 30th period.

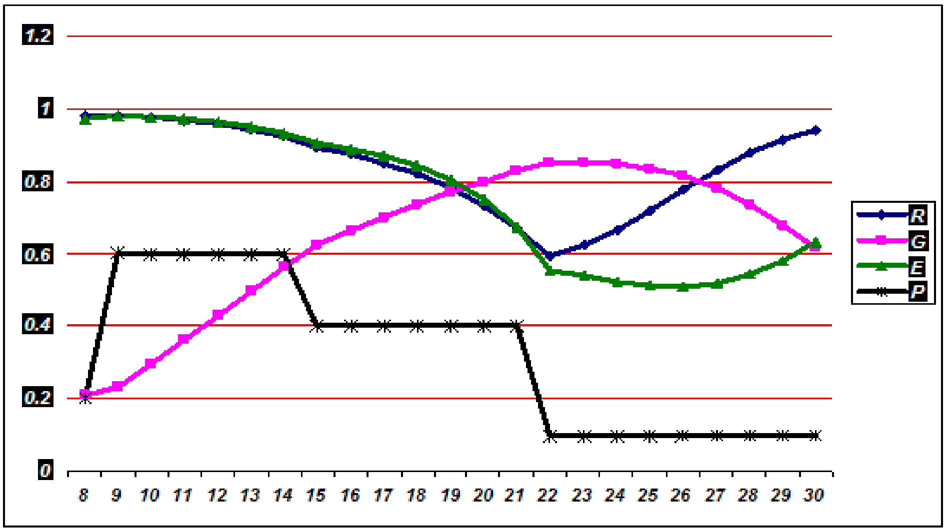
Table 8: Values for R_t, G_t, E_t , and P_t from t = 8 to 20 with Policy II

t	***Rt***	***Gt***	***Et***	***Pt***	$\mathbf{P_{Rt}}$	$\mathbf{P_{Gt}}$	$\mathbf{P_{Et}}$	$\mathbf{P_{Pt}}$
8	0.982459	0.210334	0.972764	0.200000	0.948865	0.942582	0.687032	0.316935
9	0.983348	0.230031	0.981207	0.600443	1.358007	0.832673	1.245330	0.280505
10	0.977455	0.294155	0.976651	0.600000	1.361344	0.831595	1.270826	0.281365
11	0.969434	0.361469	0.970422	0.600000	1.366538	0.829991	1.299883	0.282497
12	0.958466	0.429737	0.961724	0.600000	1.373652	0.827863	1.332015	0.284076
13	0.943393	0.496984	0.949342	0.600000	1.383404	0.825106	1.367904	0.286309
14	0.922549	0.561630	0.931358	0.600000	1.396817	0.821638	1.409167	0.289527
15	0.893505	0.622499	0.904649	0.400000	1.198011	0.868417	1.165947	0.312680
16	0.873803	0.662562	0.889729	0.400000	1.209325	0.864174	1.195051	0.316102
17	0.849000	0.700662	0.869682	0.400000	1.222900	0.859711	1.228566	0.320600
18	0.819000	0.736516	0.842365	0.400000	1.239287	0.855270	1.268650	0.326637
19	0.781000	0.769848	0.804426	0.400000	1.259058	0.851456	1.318897	0.334966
20	0.733000	0.800348	0.750492	0.400000	1.282558	0.849712	1.385565	0.346862
21	0.670824	0.827589	0.671868	0.400000	1.309136	0.853452	1.480173	0.364605
22	0.592935	0.850861	0.555073	0.100000	0.903319	0.989016	1.052538	0.444838
23	0.623667	0.852372	0.538169	0.100000	0.862535	1.032622	1.046505	0.442119
24	0.665488	0.847942	0.522884	0.100000	0.816218	1.086313	1.031791	0.436992
25	0.717205	0.835956	0.512216	0.100000	0.769266	1.145911	1.007416	0.429291
26	0.774375	0.814384	0.509681	0.100000	0.728038	1.202603	0.973874	0.419453
27	0.830142	0.781201	0.518735	0.100000	0.698330	1.244595	0.932872	0.408350
28	0.878095	0.735416	0.542102	0.100000	0.683546	1.261875	0.886463	0.396794
29	0.914973	0.678549	0.581129	0.100000	0.684196	1.250939	0.836725	0.385193
30	0.941013	0.615628	0.634981	0.100000	0.698387	1.212606	0.786348	0.373693

An Economics Application: some preliminary thoughts

The model and examples presented above have been highly simplified to demonstrate the key features of the dynamic systems approach and its usefulness in policy analysis. In general, such approach requires a substantive knowledge of the problem at hand and a method of structuring and organizing knowledge about the problem. In addition, one must decide what factors are important and must be included in the analysis. It involves keeping track simultaneously with all the important relationships once they have been sorted out. As such, computer (simulation) modelling is usually required.

Figure 4: Changes in R_t, G_t, E_t , and P_t from t = 8 to 30 with Policy II



As demonstrated in the proceeding sections, the phases of building a dynamic systems model include: problem definition, system conceptualization, model representation, data collection, policy design, and evaluation. The approach offers the advantage of being able to visualize and understand the effects of program and policy changes prior to implementation so that costly, ill-considered (often ideological and political) policy choices can be avoided.

The rest of this paper shows how this approach can be applied to an economic framework for policy analysis.

Human Capital

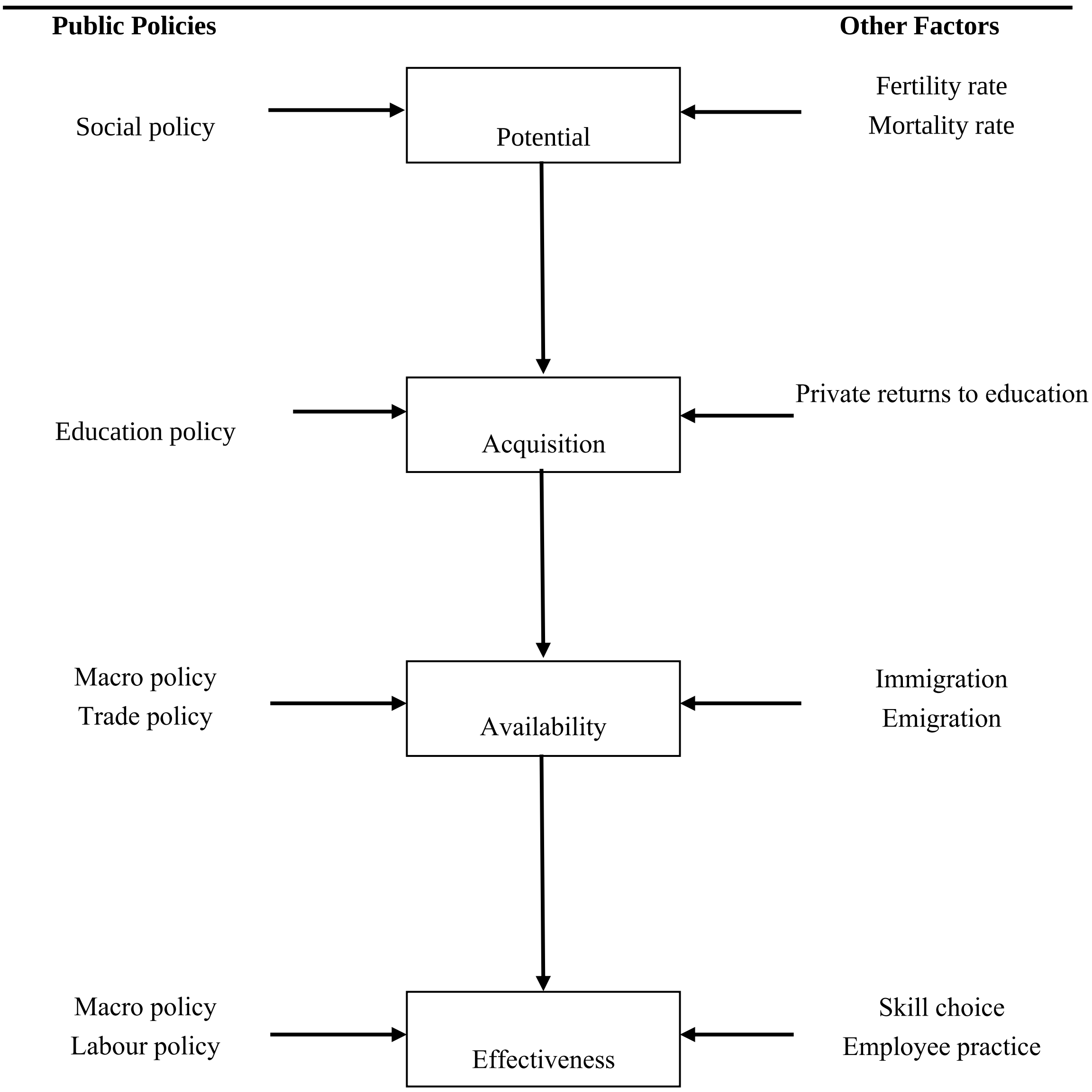
Human capital is becoming increasingly important in today's knowledge-based economy. However, existing definitions of human capital are too narrow to fully capture the implications of public policies on human capital formation and utilization.

Ruggeri and Yu [2000] propose a broad definition of human capital which includes four dimensions: (a) potential, (b) acquisition, (c) availability, and (d) effectiveness. The potential dimension highlights two fundamental aspects: the production of the pool of agents who may acquire human capital and the conditions and institutions that may affect the ability of those agents to acquire human capital in the future; Acquisition is associated with the concept of human capital incorporated in models of endogenous growth; Availability represents the amount and quality of human capital that can be used for productive purposes. Lastly, and effectiveness includes both utilization and performance.

A diagrammatic exposition of the dynamics of human capital formation and utilization is presented in Figure 5. This figure highlights three major aspects of human capital.

1. The production, development and effective utilization of human capital is a multi-faceted process involving complex interactions between private decisions and public policies.
2. Different policies affect human capital formation at different stages. Both social and economic policies affect human capital formation and utilization.
3. The social nature of human capital requires a re-thinking of social policies. In particular, it requires a deeper understanding of the interactions between social and economic policies within this framework.

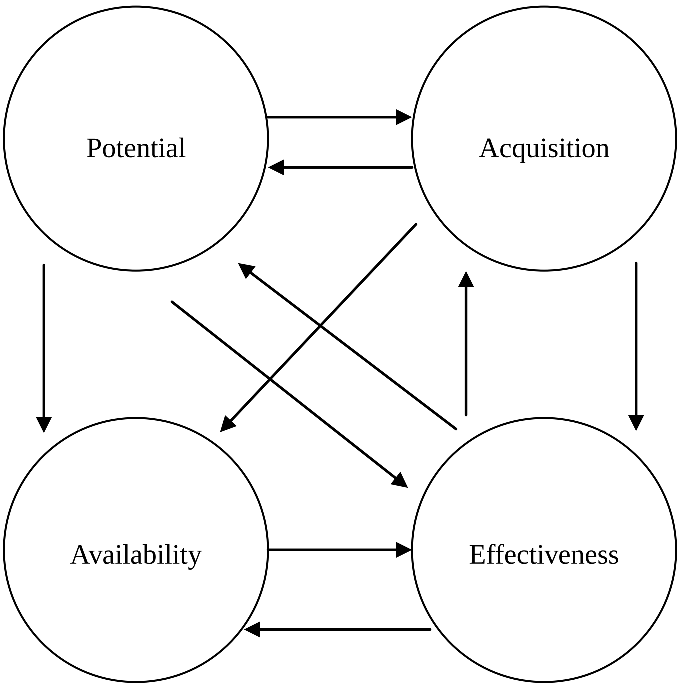
Figure 5: Dimensions of Human Capital and Policy Policies



To analyze the impact of different policies on human capital, it is necessary to view the entire framework as a system since targeted public policy can affect one or several of the dimensions listed above and policies are likely to have indirect effects which may in turn further impact specific dimensions of human capital.

In light of the proceeding discussions on dynamic systems models, it seems appropriate to use the systems approach to evaluate human capital policies. Figure 6 shows a preliminary feedback circles for the four dimensions of human capital.

Figure 6: System for Dimensions of Human Capital



Conclusion

This paper presented a simple model of three variables interacting with each other within a dynamic system. A numerical example was simulated to demonstrate how the system variables change overtime and how policy interventions can be used to stabilize the system. It also attempted to apply this model to a dynamic human capital framework developed by Ruggeri and Yu. Clearly, more work is needed to fully develop this model for policy analysis.

References

Borjas, G., & Hilton, L. (1996),. “Immigration and the welfare state: Immigrant participation in mean-tested entitlement programs.” *Quarterly Journal of Economics, 111,* 575–604.

Brooks-Gunn, J., & Duncan, G. J. (1997),. “The effects of poverty on children.”, *The Future of Children, 7,* 55–71.

Cao, J., Bennett, G., & Zhang, K. (2000),. “Direct execution simulation of load balancing algorithms with real workload distribution.”, *Journal of Systems and Software, 54*(3), 227−237.

Daneke, G. A. (1990). “Policy evaluation in an evolving world: Toward an advanced systems perspective.” In S. S. Nagel (Ed.), *Policy theory and policy evaluation: Concepts, knowledge, causes, and norms* (pp. 43–59). New York, NY: Greenwood.

Dorny, C. N. (1993). Understanding dynamic systems: Approaches to modeling, analysis, and design. Englewood Cliffs, NJ: Prentice-Hall.

Etzioni, A. (1970), “Indicators of the capacities for societal guidance.”, *Annals of the American Academy of Political and Social Science, 388,* 25−34.

Forrester, J. W. (1961). *Industrial dynamics.* Cambridge, MA: MIT Press.

Forrester, J. W. (1968). *Principles of systems*. Cambridge, MA: MIT Press.

Forrester, J. W. (1973). *World dynamics.* Cambridge, MA: MIT Press.

Forrester, J. W. (1975). *Collected papers of Jay W. Forrester.* Cambridge, MA: Wright-Allen.

Hanneman, R. A. (1995), “Simulation modeling and theoretical analysis in sociology.”, *Sociological Perspectives, 38*(4), 457−462.

Hanneman, R. A., & Patrick, S. (1997). On the uses of computer-assisted simulation modeling in the social sciences. *Sociological Research Online, 2*(2). Retrieved October 16, 2005, from http://www.socresonline.org.uk/ socresonline/2/2/5.html.

Levine, R. L., Van Sell, M., & Rubin, B. (1992), “System dynamics and the analysis of feedback processes in social and behavioral systems.” In R. L. Levine & H. E. Fitzgerald (Eds.), *Analysis of dynamic psychological systems: Vol. 1. Basic approaches to general systems, dynamic systems, and cybernetics* (pp. 145–266). New York, NY: Plenum.

Lewis, M. D. (2000), “The promise of dynamic systems theories for an integrated account of human development.”, *Child Development, 71,* 36–43.

Macy, M. W., & Willer, R. (2002), “From factors to actors: Computational sociology and agent-based modeling. “, *Annual Review of Sociology, 28,* 143−166.

Mitchell, A., & Shore, R. (1999),. *Next steps toward quality in early care and education: A report commissioned by the Early Childhood Funder Collaborative.* New York, NY: Carnegie Corporation of New York and St. Louis: The Danforth Foundation.

Ruggeri, G.C and Weiqiu Yu (2000) “On the Dimensions of Human Capital: An Analytical Framework”, *Atlantic Canada Economics Association Papers,* Vol.29, 2001, p.89-102

Schneier, E. (1970), "The intelligence of congress: Information and public-policy patterns.", *Annals of the American Academy of Political and Social Science, 388,* 14−24.

Shannon, R. E. (1975), *Systems simulation: The art and science.* Englewood Cliffs, NJ: Prentice-Hall.

Springer,M. (1970), "Social indicators, reports, and accounts: Toward the management of society.", *Annals of the American Academy of Political and Social Science, 388,* 1−13.

Thelen, E., & Smith, L. B. (1994). *A dynamic systems approach to the development of cognition and action.* Cambridge, MA: Bradford Books/MIT Press.

Thelen, E., & Smith, L. B. (1998), "Dynamic systems theories." In W. Damon (Ed.), *Handbook of child psychology: Vol. 1. Theoretical models of human development* (pp. 563–634). New York, NY: Plenum.

Zulch, G., Rinn, A., & Strate, O. (2001), "Dynamic analysis of changes in decisional structures of production systems.", *International Journal of Production Economics, 69*(2), 239−252.