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A Simulation-Based Decision-Support Model and Exercises for Universities

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Abstract*:* This paper presents a system dynamics-based decision-support model for universities so as to simulate the dynamic trajectory of key decision variables, namely teaching performance and research performance, and exemplify the design of optimal policies that enable universities to achieve certain desired objectives. The paper constructs a simple dynamic-stochastic model with properly specified adjustment dynamics and employs a system dynamics method to simulate the trajectories in question and to optimize the relevant parameter values. Examples presented in the paper could easily be extended to analyze the effects of a variety of factors, such as academic capital, physical capital or income, on teaching performance and research performance. The model could be generalized to take into account the possible and potentially highly complex interrelations among different fields.

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1. Introduction

Science and technology are among the driving forces in the known human history that have shaped the trajectory of human development in a profound manner. However primitive the early apparatus and associated human knowledge may have been, the resulting effects on the human endeavor have been quite significant, transforming the ways of living and the very forms of human existence throughout history. The transformations in question led to new epochs in human history in such a way that the transition from one epoch to another was almost always associated with new forms of apparatus/technology and knowledge.

The production, reproduction and development of new knowledge and apparatus have always been a complicated dynamic process in which many actors, factors and institutions played interactive and interrelated roles. Among these institutions are universities or university-like institutions which preserved, revised, produced and disseminated the evolving forms of knowledge, especially, in the modern age.

There are many works in the contemporary literature, which explore a wide range of issues associated with universities. Among these are Barlas & Diker (2000), Barlas, Diker, Polat (1997), Bowles (1967), Christensen (2011), Clarke, Hough & Stewart (1984), Feldman, Feller, Bercovitz & Burton (2002), Gerard (2003), Goldman & Scardamalia (2013), Hamelman (1970), Hopkins (1971), Jaffe (1989), Kara (2007, 2013a, 2013b), Knott & Payn (2004), Kretek, Dragsic & Kehm (2013), Spencer (2001), Steiner, Sundström & Sammalisto (2013), Tyagi, Moore & Taylor III (1988) and Walton, Tornatzky & Eveland (1986).

Topics covered and explored in the literature include, but are not limited to, the issues of governance (Knott & Payn (2004), Kretek, Dragsic & Kehm (2013), Christensen (2011), Gerard (2003)), the efficient allocation of resources (Bowles (1967)), the computerized decision support systems for funds management (Tyagi, Moore & Taylor III (1988)), system-theoretic/system-analytic approaches to the higher educational processes (Hamelman (1970), Clarke, Hough & Stewart (1984), Barlas & Diker (2000), Barlas, Diker, Polat (1997), Kara (2011, 2013a, 2013b)), the questions of image, identity and reputation (Steiner, Sundström & Sammalisto (2013)), research and innovation/technology (Jaffe (1989), Walton, Tornatzky & Eveland (1986), Feldman, Feller, Bercovitz & Burton (2002) and Spencer (2001)), the use of large-scale simulation models for university planning (Hopkins (1971)) and managing, applying and creating knowledge in the information age (Goldman & Scardamalia (2013)).

Works in question employ particularly-chosen methods which facilitate the analysis of the issues under investigation. The spectrum of the methods is fairly rich, ranging from system dynamics to econometrics. One can easily observe, in the literature, separate uses of the methods as well as creative combinations of them. The diversity of the methods employed greatly contributes to the “range” as well as the “reach” of the coverage of the works exemplified above.

As far-ranging as the coverage of the topics in the literature may be, there are many essential dimensions of university-related research that need further and in-depth explorations. One such dimension is the design, in the context of decision support problems, of optimal policies that are conducive to the development of intellectual (academic) human capital and creative research.

In this paper, we will develop a simple system dynamics-based decision support model that will exemplify the design of such policies. The second section of the paper will develop the model. The third section will present the steps for model-based simulations and optimization. The main points will be summarized in the concluding section.

2. The Model

Consider a representative university with n departments, each of which is associated with a scientific discipline. Each discipline consists of a number of fields in which scholars engage in teaching and research. The quantity demanded for a particular teaching service i in a field at time t (Q^{DT}_{it}) depends on the teaching performance for service i at time t (x_{it}), the relative price of the service i at time t (RP_{it}), the income(s) of the customers of service i at time t (M_{it}), the level of academic capital of the providers of service i at time t (AC_{it}) and the level of physical capital of the providers of service i at time t (PC_{it}).

i.e., $Q^{DT}_{it} = f^{D} (x_{it}, RP_{it}, M_{it}, AC_{it}, PC_{it})$,

which is a demand function for the teaching service i. $RP_{it} \in (0,\infty)$, $M_{it} \in (0,\infty)$. By construction, x_{it}, AC_{ti} and PC_{it} take on values between 0 and 7, i.e.,

$x_{it} \in (0,7]$, $AC_{ti} \in (0,7]$,and $PC_{it} \in (0,7]$. $Q^{DT}_{it} \in (0,\infty)$ (For measurement, and alternative measurement, of variables, see the appendix).

Let Q^{ST}_{it} denote the quantity supplied for the teaching service i at time t, which depends on the teaching performance for service i at time t (x_{it}), the relative price of the service i at time t (RP_{it}), the level of academic capital of the providers of service i at time t (AC_{it}) and the level of physical capital of the providers of service i at time t (PC_{it}).

i.e., $Q^{ST}_{it} = f^S (x_{it}, RP_{it}, AC_{it}, PC_{it})$.
$Q^{ST}_{it} \in (0,\infty)$.

For simplicity, we will assume that the demand and supply functions are linear:

$$Q^{DT}_{it} = \alpha_0 + \alpha_1 x_{it} + \alpha_2 RP_{it} + \alpha_3 M_{it} + \alpha_4 AC_{it} + \alpha_5 PC_{it} + u_{it}$$

and

$$Q^{ST}_{it} = \beta_0 + \beta_1 x_{it} + \beta_2 RP_{it} + \beta_3 AC_{it} + \beta_4 PC_{it} + v_{it},$$

where u_{it} and v_{it} are independent normally distributed (white noise) stochastic terms uncorrelated over time. They have zero means and constant variances σ_{ui}^2 and σ_{vi}^2 respectively.

To model the trajectory of the teaching performance over time, we will assume that the movement over time of the teaching performance is proportional to the excess demand for performance,

i.e., $x_{it+1} - x_t = k\,(Q^{DT}_{it} - Q^{ST}_{it})$,

where k is the coefficient of adjustment.

This is nothing but a dynamic adjustment equation for the teaching performance. Substituting the functional expressions (forms) for Q^{DT}_{it} and Q^{ST}_{it} specified above, setting the values ofRP_{it}, M_{it}, AC_{it} and PC_{it} to their average values RP_{it}^{avr}, M_{it}^{avr}, AC_{it}^{avr} and PC_{it}^{avr}, and rearranging the terms in the equation, we get,

$$\begin{aligned} x_{it+1} + (1-k(\alpha_1 - \beta_1))\, x_{it} = \mathrm{k}(&\alpha_0 - \beta_0 + (\alpha_2 - \beta_2)\, RP_{it}^{avr} \\ &+ \alpha_3 M_{it}^{avr} + (\alpha_4 - \beta_3) AC_{it}^{avr} \\ &+ (\alpha_5 - \beta_4) PC_{it}^{avr} + u_{it} - v_{it}), \end{aligned}$$

which is a one of the stochastic difference equations that will be employed in the simulations in the third section.

Here the model is meant to capture some essential features of the system, not the idiosyncratic properties that could differ across universities (and across the world) quite extensively. Peculiar features of a system that may be chosen for empirical investigation may need to be properly incorporated into the model and the adjustment mechanisms. To exemplify how that could be done, consider politically motivated interventions into the supply side of teaching services, which could characterize, however differently, a wide range of publicly-provided teaching services. Interventions could take many different forms, one example of which could be a pressure to increase the provision of services, irrespective (and often in excess of) what underlying factors entail. Suppose that the politically motivated component of the services takes a value of x_0, at t=0, and grows over time with a rate w, which has a constant component, w_c, and a stochastic component, w_s. Thus, the politically-motivated component of x_{it} would be $x_0(1+w)^t$. Incorporating this component into the model, the adjustment dynamic takes the form,

$$\begin{aligned} x_{it+1} + (1-k(\alpha_1 - \beta_1))\, x_{it} = k(\alpha_0 - (\beta_0 + x_0(1+w)^t) &+ (\alpha_2 - \beta_2)\, RP_{it}^{avr} \\ &+ \alpha_3 M_{it}^{avr} + (\alpha_4 - \beta_3) AC_{it}^{avr} \\ &+ (\alpha_5 - \beta_4) PC_{it}^{avr} + u_{it} - v_{it}), \end{aligned}$$

which is the revised stochastic difference equation that could be used for political factor-inclusive simulations.

Regarding the market for research, we will propose the following set-up. The quantity demanded for a particular (abstract or applied) research service j in a field at time t (Q^{DR}_{jt}) depends on the research performance for service j at time t (y_{jt}), the relative price of the service j at time t (RP_{jt}), the income(s) of the customers[2] of service j at time t (M_{jt}), the level of academic capital of the providers of service j at time t (AC_{jt}) and the level of physical capital of the providers of service j at time t (PC_{jt}).

i.e., $Q^{DR}_{jt} = g^R (y_{jt}, RP_{jt}, M_{jt}, AC_{jt}, PC_{jt})$, j=1,…,s.

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[2] Customers of research services could be firms, institutions (including universities) and individuals.

which is a demand function for the research service j. $RP_{jt} \in (0,\infty)$, $M_{jt} \in (0,\infty)$. By construction, y_{jt}, AC_{jt} and PC_{jt} take on values between 0 and 7, i.e., $y_{jt} \in (0,7]$, $AC_{jt} \in (0,7]$,and $PC_{jt} \in (0,7]$. $Q^{DR}_{jt} \in (0,\infty)$.

Let Q^{SR}_{jt} denote the quantity supplied for the research service j at time t, which depends on the research performance for service j at time t (y_{jt}), the relative price of the service j at time t (RP_{jt}), the level of academic capital of the providers of service j at time t (AC_{jt}) and the level of physical capital of the providers of service j at time t (PC_{jt}).

i.e., $Q^{SR}_{jt} = g^S (y_{jt}, RP_{jt}, AC_{jt}, PC_{jt})$.
$Q^{SR}_{jt} \in (0,\infty)$.

For simplicity, we will assume that the demand and supply functions are linear:

$$Q^{DR}_{jt} = \theta_0 + \theta_1 y_{jt} + \theta_2 RP_{jt} + \theta_3 M_{jt} + \theta_4 AC_{jt} + \theta_5 PC_{jt} + u_{jt}$$

and

$$Q^{SR}_{jt} = \delta_0 + \delta_1 x_{jt} + \delta_2 RP_{jt} + \delta_3 AC_{jt} + \delta_4 PC_{jt} + v_{jt},$$

where u_{jt} and v_{jt} are independent normally distributed (white noise) stochastic terms uncorrelated over time. They have zero means and constant variances σ_{uj}^2 and σ_{vj}^2 respectively.

To model the trajectory of the research performance over time, we will assume that the movement over time of the research performance is proportional to the excess demand for performance,

i.e., $y_{jt+1} - y_{jt} = k^* (Q^{DR}_{jt} - Q^{SR}_{jt})$,

where k^* is the coefficient of adjustment.

This is nothing but a dynamic adjustment equation for the research performance. Substituting the functional expressions (forms) for Q^{DR}_{jt} and Q^{SR}_{jt} specified above, setting the values of RP_{jt}, M_{jt}, AC_{it} and PC_{jt} to their average values RP_{jt}^{avr}, M_{jt}^{avr}, AC_{it}^{avr} and PC_{it}^{avr}, and rearranging the terms in the equation, we get,

$$\begin{aligned} y_{jt+1} + (1-k^*(\theta_1 - \delta_1))\, y_{jt} = {} & k^*(\theta_0 - \delta_0 + (\theta_2 - \delta_2) RP_{jt}^{avr} \\ & + \theta_3 M_{jt}^{avr} + (\theta_4 - \delta_3) AC_{jt}^{avr} \\ & + (\theta_5 - \delta_4) PC_{jt}^{avr} + u_{jt} - v_{jt}), \end{aligned}$$

which is the stochastic difference equation describing the movement of the research performance over time.

The stochastic difference equations derived above will be the basis of the simulations that will be undertaken in the following section.

3. Simulations

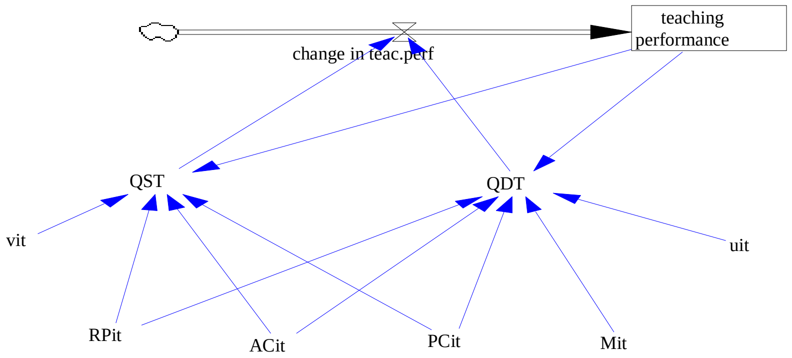
3.1. Simulations for Teaching and Research Performances[3]

We will employ a system dynamics procedure to carry out separate simulations for teaching and research performances. Joint system dynamics simulations will be the subject of the subsection III.2 below.

System dynamics method makes use of stock, flow and auxiliary variables and requires that the feedback relations/structures involving these variables be properly specified. In our model and associated sub-models, at least one of the key variables, namely teaching performance and research performance is taken to be the stock variable. The flow variable is the change in the stock variable. Other variables are of the auxiliary type helping to specify the causal connections as well as the feedback relations within the system.

A simulation diagram describing the feedback-relations embodied in the model (and the associated stochastic difference equation) for the teaching performance is as follows:

Simulation Diagram: The teaching performance



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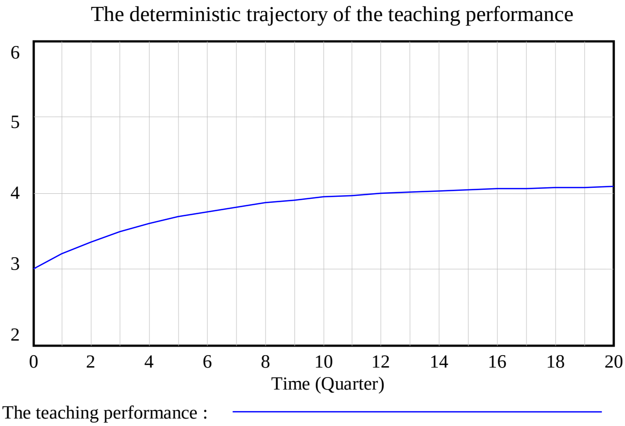
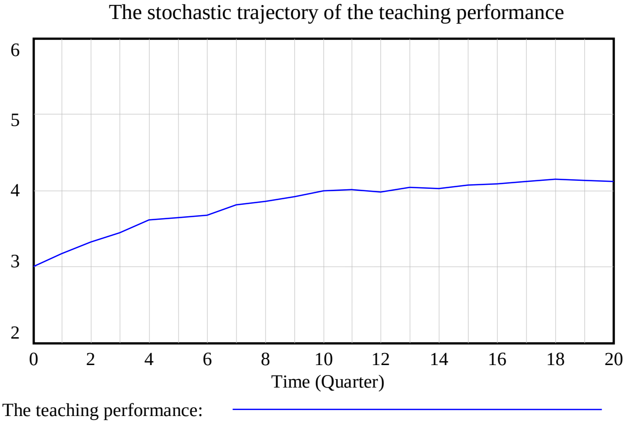
[3] A number of software packages, such as Vensim and Matlab, could be used to undertake the simulations in this paper. In this paper, the choice was Vensim.

For simulation purposes, let: $\alpha_0 = 0$, $\alpha_1 = 0.2$, $\alpha_2 = -2$, $\alpha_3 = 0.8$, $\alpha_4 = 0.4$, $\alpha_5 = 0.4$, $\beta_0 = 0$, $\beta_1 = 0.7$, $\beta_2 = 0.5$, $\beta_3 = 0.3$, $\beta_4 = 0.3$, $k = 0.35$, $RP_{it}^{avr} = 1.1$, $M_{it}^{avr} = 5$, $AC_{it}^{avr} = 0.4$ and $PC_{it}^{avr} = 0.4$. The initial $x_{it} = 3$. The simulated deterministic trajectory for the teaching performance is described below.

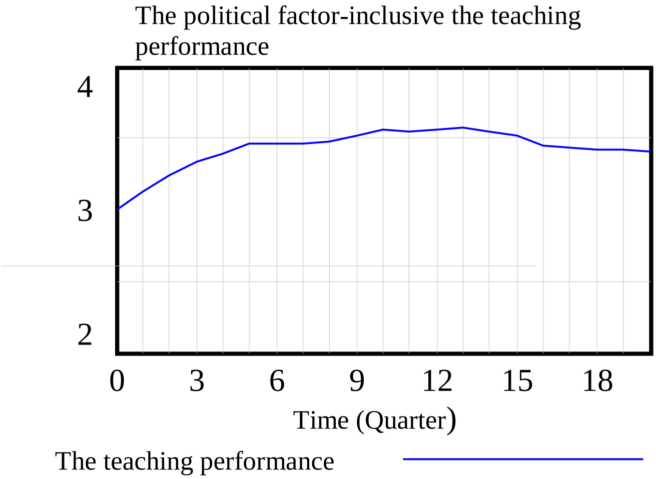


Given the parameter values and starting from an initial point where $x_{it} = 3$, the teaching performance increases and reaches an equilibrium value of 4.1. This deterministic trajectory, however, does not hold when we allow the presence of stochastic terms, u_{it} and v_{it}. Suppose that $\sigma_{ui} = 0.1$ and $\sigma_{vi} = 0.15$. The simulated stochastic trajectory for the teaching performance is as follows:



The presence of the stochastic terms has induced fluctuations around the deterministic trend. Depending on the nature and magnitude of these terms, these fluctuations may well be significant.

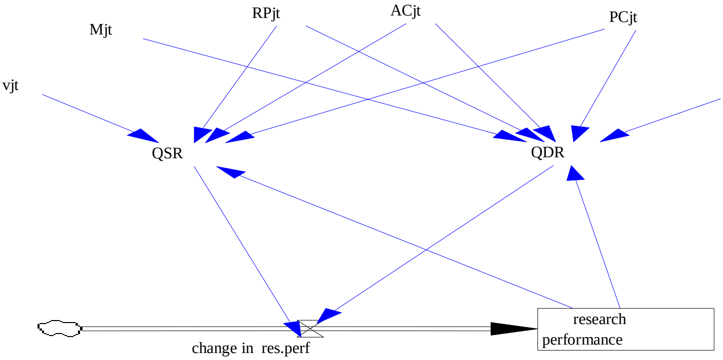
For a political factor-inclusive simulation of the teaching performance, let x_0 =1, w_c=0.01. Let w_s be a stochastic term with mean = zero and standard deviation = 0.005. The simulated trajectory of the political factor-inclusive teaching performance is as follows:



A politically-induced increase in the provision of services is likely to lead to reductions in the teaching performance, through perhaps reductions in quality, as exemplified by the diagram.

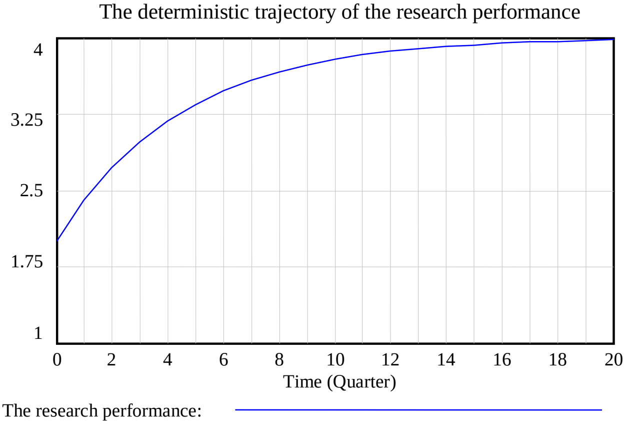
We will repeat the simulation exercise for the research performance as well.

Simulation Diagram: The research performance

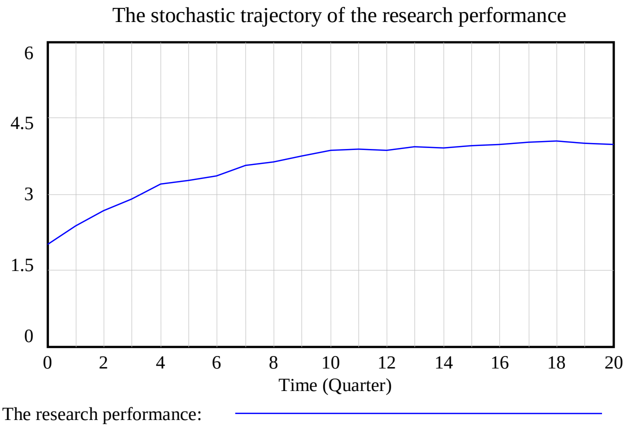


For simulation purposes, let: $\theta_0 = 0$, $\theta_1 = 0.2$, $\theta_2 = -2$, $\theta_3 = 0.8$, $\theta_4 = 0.4$, $\theta_5 = 0.4$,

$\delta_0 = 0$, $\delta_1 = 0.7$, $\delta_2 = 0.5$, $\delta_3 = 0.3$, $\delta_4 = 0.3$, $k^* = 0.35$, $RP_{jt}^{avr} = 1.1$, $M_{jt}^{avr} = 5$, $AC_{jt}^{avr} = 0.4$ and $PC_{jt}^{avr} = 0.4$. The initial $y_{jt} = 3$. The simulated deterministic trajectory for the research performance is described below.


The deterministic trajectory of the research performance

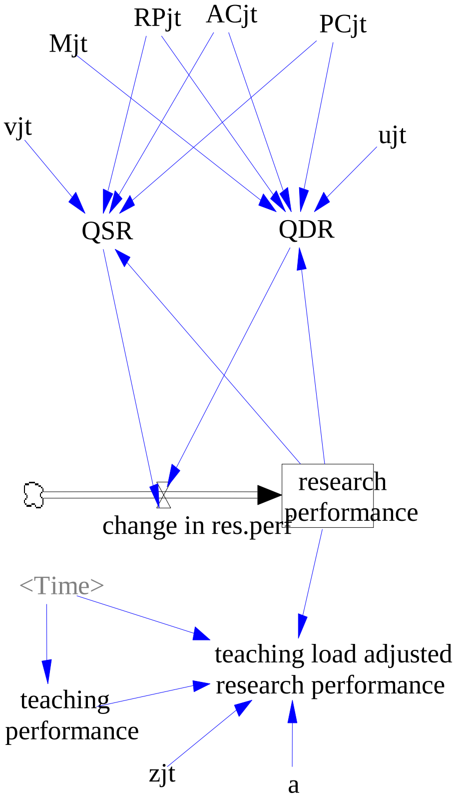
In the absence of any uncertain factors, and starting from an initial point where $y_{it} = 2$, the research performance reaches the level of 4. In the presence of uncertain factors represented by u_{jt} and v_{jt}, the trajectory changes. Suppose that $\sigma_{uj} = 0.15$ and $\sigma_{vj} = 0.15$. The simulated stochastic trajectory for the research performance is as follows:



Clearly, the stochastic factors lead to fluctuations in the trajectory of the research performance, which need not exactly reach the level of the deterministic equilibrium.

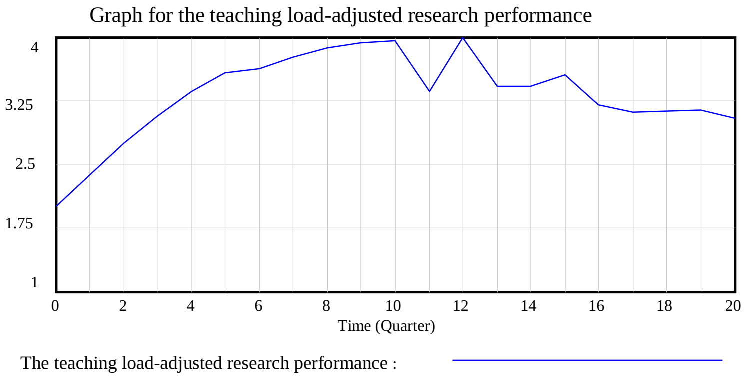
We have chosen a subset of the possible factors that could potentially influence, in a partial framework, the trajectories of the key variables. Clearly there may be other factors that could play a role in shaping the trajectories in question by helping to generate kinks, discontinuities or structural changes/breaks. For instance, course-loads (teaching loads) beyond a certain level are likely to have adverse effects on the research performance, inducing a qualitatively different trajectory. Below, we present a simulation exercise for a course load-adjusted teaching performance.

Simulation diagram for the teaching-load adjusted research performance



Suppose that beyond a certain level, $x_{it} = x_{it}^{*}$, the teaching load adjusted research performance, $y_{jt'} = (1\text{-at})y_{jt} + z_{jt}$, where the last term is meant to capture the stochastic fluctuations in $y_{jt'}$.

For simulation purposes, let, in addition to the previous parameter values, $x_{it}^{*} = 4$, and $a = 0.01$. Let z_{jt} be independent normally distributed stochastic terms with zero means and standard deviations that are equal to 0.2. The new trajectory is as follows:



Beyond a certain teaching load, the research performance starts decreasing over time and displays a qualitatively different behavior. This constitutes one example of such phenomena out of many possible ones. Depending on the nature and diversity of the underlying factors, trajectories could turn out to be quite complex, exhibiting a variety of different patterns.

3.2. Joint Simulations and Determination of Optimal Policy Parameters

We will now combine the models for teaching and research and add some new dimensions. Define the profit from teaching and profit from research in a field at time t in the usual “revenue minus cost” terms. The variables needed for the calculation of revenues are contained in the model. We need to provide information about costs.

Let us assume that performance figures represent proxies for the quantity of services, and suppose that costs are quadratic of the following forms:

Cost of teaching$_{it}$= $c_1.x_{it}^2$

and

Cost of research$_{jt}$ = $c_2.y_{jt}^2$,

where c_1 and c_2 are positive real numbers.

Suppose that a fraction of the total profits, say z, is reinvested for the purpose of expanding academic capital in teaching and research.[4] Assume that r is the fraction of the total profit that is reinvested in the capital for teaching, and z-r is the fraction for research. Thus,

The investment in teaching in a field at time t (I^T_t) is:

I^T_t = r. Total profit from teaching and research in the relevant field at time t.

Similarly,

The investment in research in a field at time t (I^R_t) is:

I^R_t = (z-r).Total profit from teaching and research in the relevant field at time t.

Suppose that the total academic capital expansion in the field at time t ($TACE_t$) is a function of these investments and takes the following Cobb-Douglas form:

$$TACE_t = (I^T_t)^s . (I^R_t)^{1-s}.$$

We will further assume that the academic capital in teaching and research will increase by s and (1-s) times total the academic capital expansion respectively.

The representative university may have a number of goals to achieve, but for present purposes, let us assume that it attempts to find the optimal value of r that maximizes total academic capital expansion.

Below, we will present a combined simulation diagram that is suitable for:

(a) joint simulations of trajectories of the teaching performance and research performance in deterministic and stochastic settings, and

(b) determination of the optimal policy parameters such as r.

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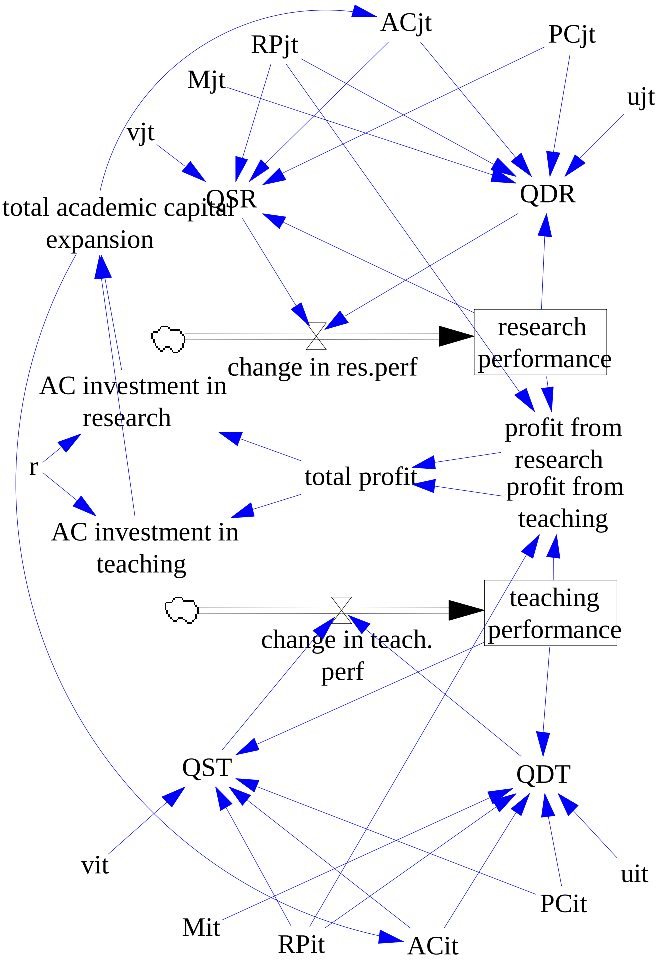
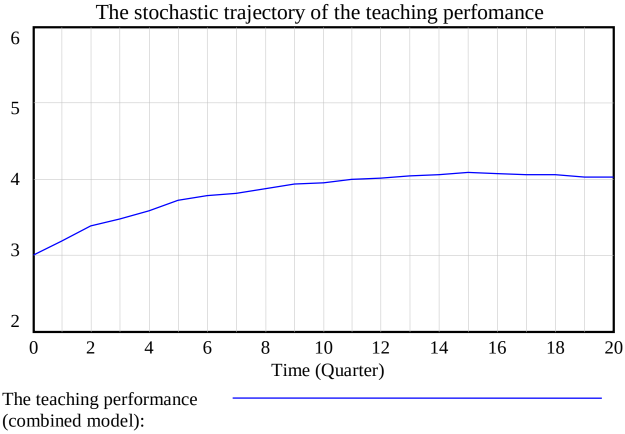
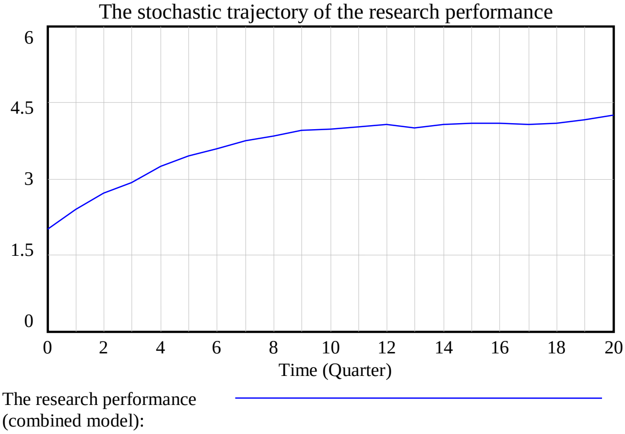
[4] The universities need not confine themselves to internal funds. They could borrow from either conventional banks or from "profit-and-loss-sharing institutions" which may however encounter some problems in financing profit-and-loss sharing projects. For a description of those problems, see Kara (2001).

Combined Simulation Diagram



For simulation purposes, assume that the previous parameter values hold. Additionally, let $c_1 = 0.12$, $c_2 = 0.1$, $z = 0.2$ and $s = 0.4$. The simulated stochastic trajectories of the teaching and research performances are as follows:





The impact of academic capital investment on the research performance appears to be more significant than the impact on the teaching performance.

On the other hand, the optimal value of r has turned out to be approximately 0.08. In other words, out of the 20% of the total profit that is set aside for investments in academic capital, 8% should be assigned to teaching and 12% should be assigned to research.

The simulation of performance trajectories and the optimality analysis would enable us to trace the effects, through the feedback processes, of a change in any of the system parameters on the system performance. This would open up new possibilities for the dynamic policy analysis about the timing and magnitude of policy interventions over time. The model could be generalized to account for a variety of related processes as well.

4. Conclusion

This paper takes a step towards making two contributions to the analysis of decision support problems in universities. First, it presents a simple way of simulating the trajectories of some of the key decision variables, namely teaching performance and research performance. Exercises could easily be extended to simulate the effects of a variety of factors, such as academic capital, physical capital or income, on the performances in question. Second, it provides a way of determining the optimal values of policy parameters.

The analysis presented in the paper could be extended in a number of ways: First, the model in the paper is a partial-equilibrium one that focuses on a representative field, and as such, it does not take into account the interrelations among different fields. Exploring those interrelations could yield new insights. Second, the optimization problem presented in the paper is a one-dimensional one. The university may have multiple objectives and multiple preferences that open the doors to multiple optimization problems, the study of which is worthy of future research.[5]

Appendix

Measurement of variables: Teaching and research performances represent “perceived successes” that could be based on a number of quantity as well as quality criteria. Academic capital represents the teaching-and/or-research-related skills, knowledge and competences of the service providers. With properly constructed questionnaires enabling evaluators (such as specialists or receivers of services) to assign ratings or grades, variables such as performance, academic capital and physical capital could be measured on such scales with 0 representing the lowest grade that could be given and 7 representing the highest.

Variables such as relative price, income, quantity demanded and quantity supplied take on positive real values. They are measured on a

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[5] For an analysis of multiple preferences in economic theory, see Kara (1996, 2009).

continuous scale. Nevertheless the values such variables take could be translated into “bands”, which are continuous intervals with lower and upper limits. For instance, the interval (0, 7] could be decomposed into hierarchically ordered intervals with the first, (0,1], representing the lowest category of values, and (6,7] representing the highest. Values higher than 7 are subsumed into the highest category. Throughout the paper, we have, sometimes, made recourse to a “band-measurement” for other variables as well.

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