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Research Article

THE NEW ALGORITHM INVOLVING MINIMUM SPANNING TREE FOR COMPUTER NETWORKS IN A GROWING COMPANY*

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Abstract

The aim of this article is to present a new algorithm based on minimum spanning trees. Minimum Spanning Trees have long been used in data mining, pattern recognition and machine learning. However, it is difficult to apply traditional minimum spanning tree algorithms to a large dataset since the time complexity of the algorithms is quadratic. The given algorithm is designed to reduce this difficulty. This application has reduced the cost.

Keywords: Graph theory, minimum spanning tree, Prim's algorithm.

Araştırma Makalesi

BÜYÜYEN BİR ŞİRKETTE BİLGİSAYAR AĞLARI İÇİN MINIMUM SPANNING TREES İÇEREN YENİ BİR ALGORİTMA

Öz

Bu makalenin amacı, Minimum Spanning Trees'ye dayalı yeni bir algoritma sunmaktır. Minimum Spanning Trees, veri madenciliği, model tanıma ve makine öğrenmede uzun süredir kullanılmaktadır. Bununla birlikte, geleneksel Minimum Spanning Trees algoritmalarını büyük bir veri kümesine uygulamak zordur. Çünkü algoritmaların zaman karmaşıklığı ikinci derecedir. Verilen algoritma bu zorluğu azaltmak için tasarlanmıştır. Bu uygulama maliyeti düşürmektedir.

Anahtar Kelimeler: Grafik teori, minimum spanning tree, Prim algoritması.

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1. INTRODUCTION

A minimum spanning tree (MST) is a spanning tree of an undirected and weighted graph such that the sum of the weights is minimized. Numerous applications have been published on the MST based on a undirected graph (Prim 1957, Kruskal 1956). As the intrinsic structure of a dataset can be roughly estimated, the MST has been broadly applied in image segmentation, cluster analysis, classification, manifold learning, density estimation, diversity estimation, and some applications of the variant problems in the area.

The MST problem, is mostly regarded as a cornerstone of Combinatorial Optimization. In the 1950s, it is commonly known that Kruskal (1956) and Prim (1957) for the first time produced algorithms on a spanning tree of a minimum length in a weighted connected graph. However, the earliest algorithms on the topic were presented by Boruvka (1926).

Trees and spanning trees represent a very fundamental and important graph structure for combinatorial optimization. Spanning trees serve as building blocks when designing telecommunications and electric power networks. Definitions of tree and spanning tree are as follows:

Given a general connected undirected graph $G=(V,E)$, a set tree in *G* is connected subgraph $T=(V',E')$ containing no cycles If $V'=V$ then *T* is a spanning tree for the graph *G*.

Due to the definitions, trees are made of one piece of line/graph and if the tree has the same number of vertices, then the one pieced has the minimum number of edges.

We can give the MST problem as follows:

Given a finite set *V* and real weight function ω on pairs of elements of *V*, find a tree *(V,T)* of minimal weight

$$\omega(T)=\sum\left[\omega(x,y):\{x,y\}\in T\right]$$

Example 1.1. (Nesetril et.al. 2001) Let *V* be a subspace of a metric space and weighted function be a distance function. Then, a solution *T* presents the shortest network connecting all points of *V*.

Example 1.2. In the Figure 1, the set $V/(G)=\{1,2,3,4\}$ denotes the set of points. Then, $E(G)=\{(1,2),(1,3),(2,4)\}$ becomes the set of edges.

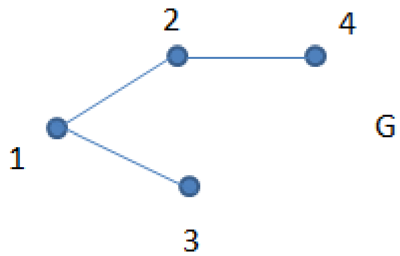

Figure 1.

Another formulation can be given as follows:

Given a undirected graph $G=(V,E)$ with real weights assigned to its edges. Find a spanning tree *(V,T)* of, $G, T \subseteq E$ with the minimal weight $\omega(T)$.

The MST problem has been solved in 1926 by Boruvka (1926a, 1926b). Boruvka (1926b) has defined this problem as follows:

In the space, we consider *n* points. The mutual distances between these *n* points are assumed to be different. The problem is to join them through the net in such a way that;

i. Any two points are joined to each other either directly or by means of some other points,

ii. The total length of the net would be the smallest.

The Boruvka's algorithm begins by first examining each vertex and adding the cheapest edge from that vertex to another in the graph, without regard to already added edges, and continues joining these groupings in a like manner until a tree spanning all vertices is completed.

Boruvka's algorithm can be given as follows:

Input: A connected graph G whose edges have distinct weights
Initialize a forest T to be a set of one-vertex trees, one for each vertex of the graph.
While T has more than one component:
For each component C of T.
Begin with an empty set of edges S
For each vertex v in C:
Find the cheapest edge from v to a vertex outside of C, and add it to S
Add the cheapest edge in S to T

Combine trees connected by edges to form bigger components
Output: T is the minimum spanning tree of G.

Then, similar algorithms have been constructed by many mathematicians. One of the most typical examples of these algorithms is the Prim's algorithm (Prim, 1957). Firstly, it arbitrarily selects a vertex as a tree, and then repeatedly adds the shortest edge that connects a new vertex to the tree, until all the vertices are included.

In Figure 2, a graph and its MST structure can be seen.

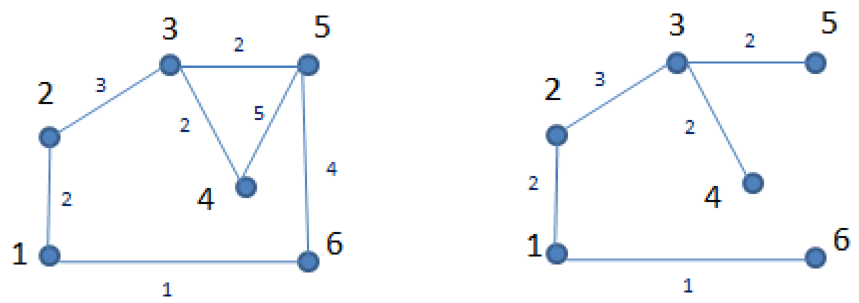

Figure 2.

The purpose of this work is to develop a new algorithm for MST. The new algorithm is implemented on an expanding network of computers.

2. ALGORITHMS

There are various algorithms developed to find the MST of a graph. It is well known that a graph can have more than one MST. One of the best known of these is the Prim algorithm.

It starts with an empty spanning tree. The idea is to maintain two sets of vertices. The first set contains the vertices already included in the MST, the other set contains the vertices not yet included. At every step, it considers all the edges that connect the two sets, and picks the minimum weight edge from these edges. After picking the edge, it moves the other endpoint of the edge to the set containing MST.

The idea behind Prim’s algorithm is simple, a spanning tree means all vertices must be connected. So the two disjoint subsets (discussed above) of vertices must be connected to make a Spanning Tree.

Algorithm 1(Prim's Algorithm):

```
let T be a single vertex x
   while (T has fewer than n vertices)
   {
      find the smallest edge connecting T to G-T
      add it to T
      }
```

or it can be given as follows:

> ***Step 1.*** *First begin with any vertex in the graph.*
>
> ***Step 2.*** *Of all of the edges incident to this vertex, select the edge with the smallest weight.*
>
> ***Step 3.*** *Repeat step 2 using the edges incident with the new vertex and that aren't already drawn.*
>
> ***Step 4.*** *Repeat until a spanning tree is created.*

It can also give the Prim's algorithm as follows:

The following codes are given by C++ program for Prim's Minimum Spanning Tree (MST) algorithm (http://scanftree.com/Data_Structure/prim\%27s-algorithm):

```
#include<stdio.h>
#include<conio.h>
int a,b,u,v,n,i,j,ne=1;
int visited[10]={0},min,mincost=0,cost[10][10];
void main()
{
   clrscr();
   printf("\nEnter the number of nodes:");
   scanf("%d",&n);
   printf("\nEnter the adjacency matrix:\n");
   for(i=1;i<=n;i++)
   for(j=1;j<=n;j++)
   {
      scanf("%d",&cost[i][j]);
      if(cost[i][j]==0)
      cost[i][j]=999;
    }
   visited[1]=1;
   printf("\n");
```

```
    while(ne < n)
{
       for(i=1,min=999;i<=n;i++)
       for(j=1;j<=n;j++)
       if(cost[i][j]< min)
       if(visited[i]!=0)
{
       min=cost[i][j];
       a=u=i;
       b=v=j;
}
       if(visited[u]==0 || visited[v]==0)
{
       printf("\n Edge %d:(%d %d) cost:%d",ne++,a,b,min);
       mincost+=min;
       visited[b]=1;
}
       cost[a][b]=cost[b][a]=999;
}
       printf("\n Minimun cost=%d",mincost);
       getch();
```

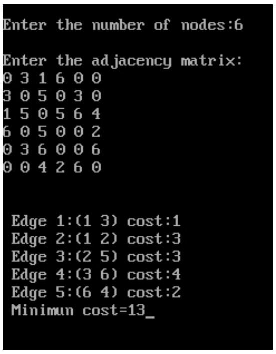

Figure 3: The output of program which is given by C++

We will find the MST that includes edges $\{e_1,e_2,\ldots, e_k\}$ of the graph G. Thus, we can solve this generalized minimum spanning problem by using the new algorithm as follows:

Algorithm 2:

Step 1. *Create the MST* T *of a graph using the Prim's algorithm. Choose one of the edges* $\{e_1,e_2,\ldots, e_k\}$.

Step 2. *If the edges* $\{e_1,e_2,\ldots, e_k\}$ *belong to* T, *then* T *is the MST. If the* *edges* $\{e_1,e_2,\ldots, e_k\}$ *doesn't belong to* T, *create a set* S *of edges that doesn't belong to* T.

Step 3. *Choose an edge from the set* S *and add to* T. *In this case, the cycle occurs in* T. *Choose the longest edge outside the edges* $\{e_1,e_2,\ldots, e_k\}$ *in this cycle and remove the longest edge from* T.

Step 4. *Remove the latest edge added to* T *from the set* S.

Step 5. *Repeat from Step 3, until* S *is an empty set.*

Theorem 2.1. Let $G=(V(G),E(G))$ be a graph and $\{e_1,e_2,...,e_k\}\subset E(G)$. Apply Algorithm 2 to graph G according to the given edge lengths. The resulting graph is the MST containing edges $\{e_1,e_2,\ldots, e_k\}$ of G.

Proof. Firstly, when Algorithm 2 is applied, it should be shown that the resulting graph is the MST. The graph T is the MST because of the *Step 1* of Algorithm 2. In the next steps of the algorithm, T is still the MST. It is well known that when an edge is added to T, the cycle is obtained. If an edge is removed, then T does not contain cycles. Then, the last graph is still the MST.

Now, it will be shown that the obtaining spanning tree at the end of the algorithm is the minimum spanning tree containing edges $\{e_1,e_2,\ldots, e_k\}$. If the graph T does not include the given edges, then one of the non-included edges is added to T in each step. Thus, the last obtained graph will include all of the edges $\{e_1,e_2,\ldots, e_k\}$.

Suppose that T' is the MST including the edges $\{e_1,e_2,\ldots, e_k\}$. If $T=T'$, then the proof is complete. Consider that $T\neq T'$. Then, there is at least one edge in the tree T and not in the tree T'. Let $e=(u,v)$ be one of these edges. Since the tree T' also contains the edges $\{e_1,e_2,\ldots, e_k\}$, the edge e cannot be one of the edges in the set $\{e_1,e_2,\ldots, e_k\}$. Then, the edge e should be one of the edges added to the graph while applying the Prim's algorithm. If the edge e is removed from T, T becomes the two-part graph. Let's denote the set of points of one of these pieces by X. Therefore, the other part of the graph can be represented by $V(G)\setminus X$ (Figure 4).

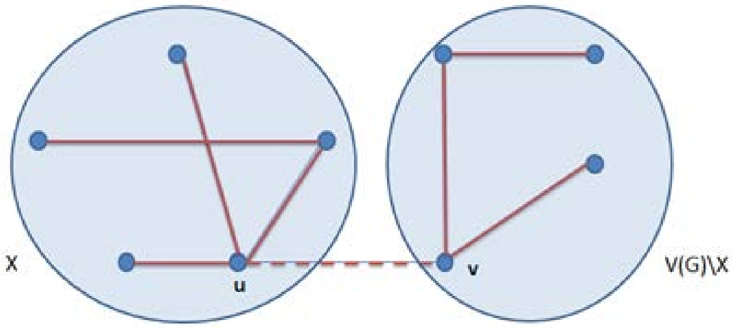

Figure 4: The set *X* and *V(G)\X* for a tree.

Add the edge *e=(u,v)* to T'. Then, a cycle will occur in the T'. Because there is a path to connect the points *u* and *v* in the T'. T' is a one-part graph. Therefore, there is an edge that connects the points of *X* to the points of $V(G)\setminus X$ in this cycle. Let edge *f* be one of these edges. Since the *e* edge is added while applying the Prim algorithm, the *e* edge must be one of the shortest edges connecting the points of *X* to the points of $V(G)\setminus X$. This means that the length of edge *e* is smaller than the length of edge *f* or equal. Let edge *e* be a smaller than edge *f* and add edge *e* to the tree T'. In this case, the cycle is obtained. Let get tree T'' by removed the edge *f* from this cycle. Then, tree T'' becomes shorter than tree \$ T'. This is a contradiction, since tree T' is the MST containing edges $\{e_1,e_2,\ldots, e_k\}$. Thus, the length of edge *f* must be equal to the length of edge *e*. So tree T'' becomes the same length as tree T'.

The edges in the tree *T* (but not in T') can be added to the tree T' without changing its weight. At the end of the process, tree T' becomes tree *T*. So the length of *T* equals the length of T'. It can be seen that tree *T* is the MST containing edges $\{e_1,e_2,\ldots, e_k\}$.

3. AN APPLICATION

In this section, we will apply this algorithm to the graph shown in Figure 5 to see how the new algorithm works.

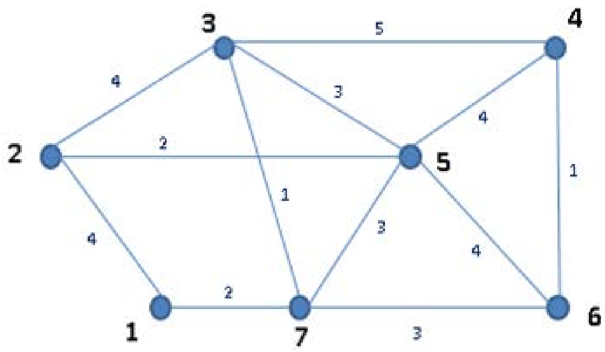

Figure 5.

Consider the edges {(1,7), (4,6), (5,4), (6,7)}. It is requested to find an MST containing these edges. According to the weights MST should also contain edges (7,3) and (5,2). However, the MST is still unique (Figure 6).

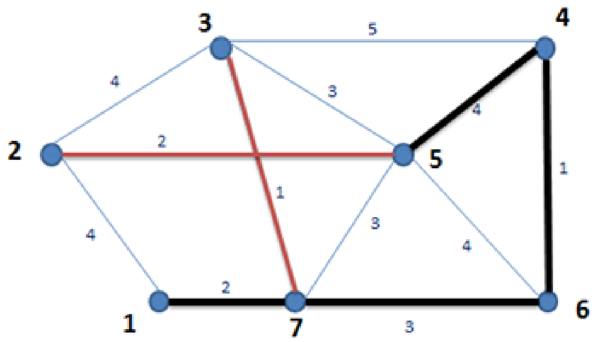

Figure 6.

Denote the tree *T* in Figure 6. Apply Algorithm 2 to tree *T*. Because of the first step of Algorithm 2, the Prim algorithm is applied to Figure 5 and an MST is found. Primarily, the tree $T = (V(T), E(T))$ is generated, where $V(T) = \{\ \}$ and $E(T) = \{\ \}$ *E*A random point is selected from the graph *G*. Assume that the point *1* is selected. Add point *1* to the tree *T*. Therefore, $V(T) = \{1\}$ and $E(T) = \{\ \}$

In the first step, the edges connecting point *1* to other points of graph *G* are investigated and the shortest of these points is selected. The shortest edge is (1,7), since its length is *2* units. The edge (1,7) and the point *7* are added to the tree *T*. Then, $V(T) = \{1, 7\}$, $E(T) = \{(1, 7)\}$ (see Figure 7).

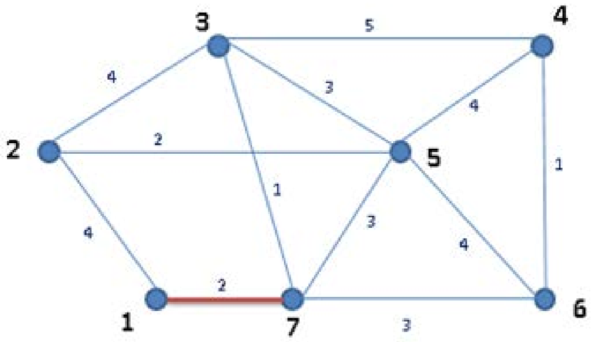

Figure 7.

In the second step, the edges connecting points of the set {1,7} to other points of the graph *G* are examined and the shortest of these points is selected. The edges are {(1,2), (7,3), (7,5), (7,6)}. The shortest edge is (7,3). The edge (7,3) and the point *3* are added to the tree *T*. Then, $V(T)=\{1,7,3\}$, $E(T)=\{(1,7),(7,3)\}$ (see Figure 8).

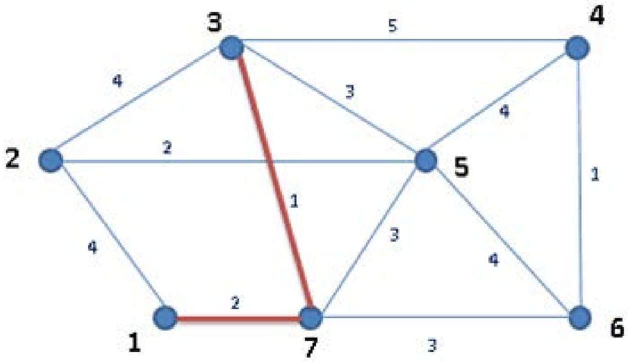

Figure 8.

For the third step, the edges connecting points of the set {1,7,3} to other points of the graph *G* are examined and the shortest of these points is selected. The edges are {(1,2), (3,2), (3,4), (3,5), (7,5), (7,6)}. The shortest edges are (3,5), (7,5), (7,6). Choose the edge (7,6). The edge (7,6) and the point *6* are added to the tree *T*. Then, *V(T)*={1,7,3,6}, E(T)={(1,7), (7,3), (7,6)} (see Figure 9).

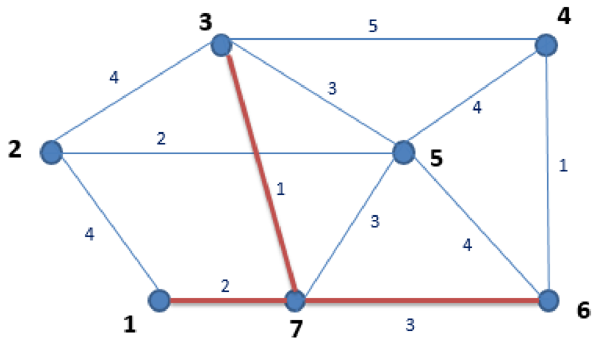

Figure 9.

In the fourth step, the edges connecting points of the set {1,7,3,6} to other points of the graph *G* are examined and the shortest of these points is selected. The edges are {(1,2), (3,2), (3,4), (3,5), (6,4), (6,5), (7,5)}. The shortest edge is (6,4). The edge (6,4) and the point *4* are added to the tree *T*. Then $V(T) = \{(1,73,6,4)\}$, (see $E(T) = \{(1,7),(7,3),(7,6),(6,4)\}$ Figure 10).

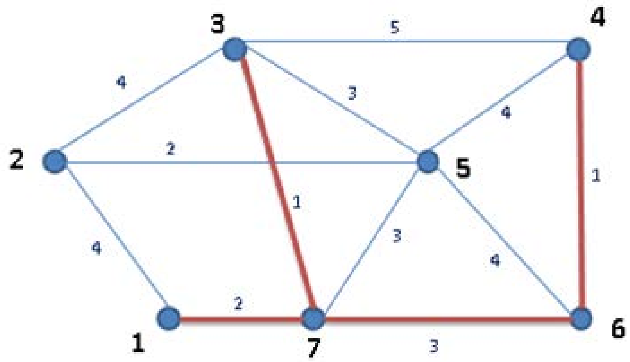

Figure 10.

In the fifth step, the edges connecting points of the set {1,7,3,6,4} to other points of the graph *G* are examined and the shortest of these points is selected. The edges are {(1,2), (3,2), (3,4), (3,5), (4,5), (6,5), (7,5)}. The shortest edges are (3,5), (7,5). Choose the edge (7,5). The edge (7,5) and the point *5* are added to the tree *T*. Then, $V(T) = \{1,7,3,6,4,5\}$, $E(T) = \{(1,7),(7,3),(7,6),(6,4),(7,5)\}$ (Figure 11).

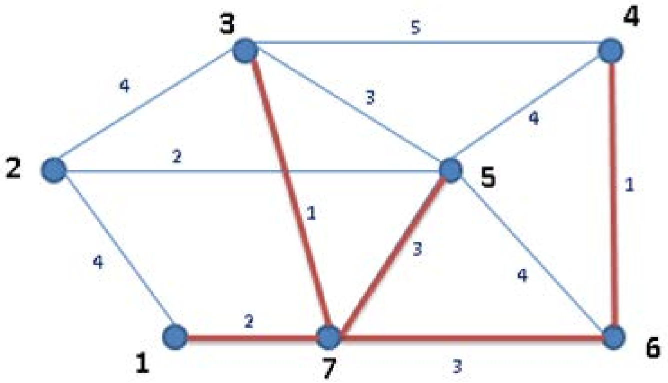

Figure 11.

For the step 6, the edges connecting points of the set {1,7,3,6,4,5} to other points of the graph *G* are examined and the shortest of these points is selected. These are {(1,2), (3,2), (3,4), (3,5), (4,5), (5,2), (6,5)}. The shortest edge is (5,2). The edge (5,2) and the point *2* are added to the tree *T*. Then, $V(T)=\{1,7,3,6,4,5,2\}$, $E(T)=\{(1,7),(7,3),(7,6),(6,4),(7,5),(5,2)\}$ (see Figure 12).

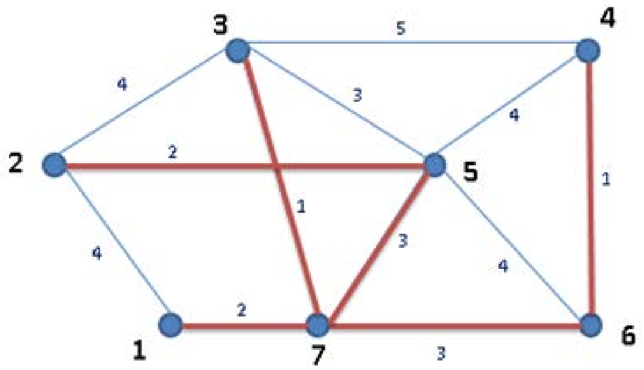

Figure 12.

At this point in the process, the points number of *T* equal to the points number of *G*. Thus, the Prim's algorithm will end up. Obtained graph at the end of the process is an MST of *G*.

Let's start with the second step of the algorithm. It is checked whether the tree *T* contains edges {(1,7), (4,6), (5,4), (6,7)}. The edge (5,4) is not found in the tree *T*. Then, S={(5,4)}. According to the third step of the algorithm, an edge is selected from the set *S*. This is the edge (5,4). The edge (5,4) is added to the tree *T* (Figure 13). In this case, the points *4*, *5*, *7* and *6* generate a cycle. In this cycle, find the longest edge except for the edges {(1,7), (4,6), (5,4), (6,7)}. This is the edge (5,7), since its length is *3* units. The edge (5,7) is deleted from tree *T*.

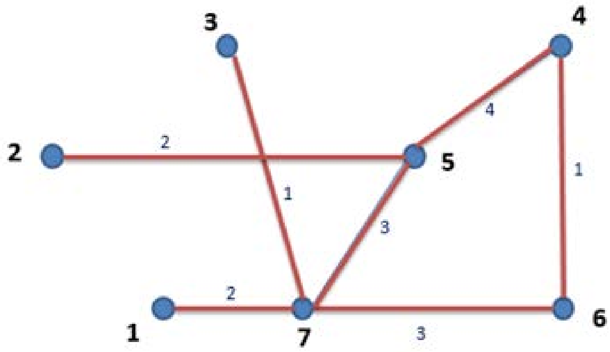

Figure 13.

In the last step of the algorithm, the edge (5,4) is removed from the set *S*. The set *S* becomes an empty set and the algorithm ends (Figure 14).

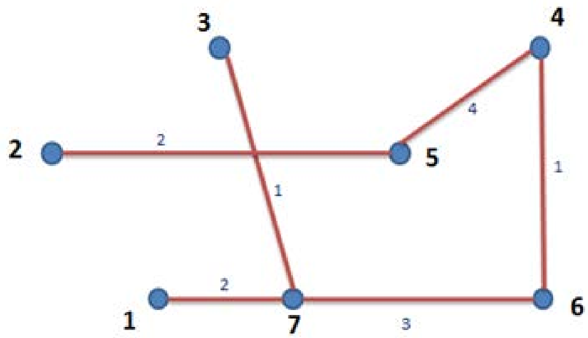

Figure 14.

4. CONCLUSION

In this work, a minimum spanning tree is studied and a new algorithm is given. The new algorithm uses the Prim algorithm as the first step. The given algorithm is applied on a sample. The MST has been generated for a company's computer systems. The MST generated by the new algorithm has a significant contribution to reducing the cost.

In this problem, the MST can be easily found because the number of points and edges are small. It is obvious that it will be difficult to find the MST when the number of points and edges increases. The new algorithm will solve the problem easily and quickly even if the number of points and edges increases.

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Research Article

SIMULATIONS OF RESEARCH PERFORMANCE IN CROSS-DISCIPLINARY CONTEXTS: A MODEL AND AN APPLICATION*

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Abstract

The purpose of this paper is to construct a model of research performance, based on a demand-and-supply set-up, in a cross-disciplinary context and simulate the trajectory of research performances. We take into account the effects of human capital and research technology as well as interactions among different disciplines/subjects so as to theorize about possible shapes of these trajectories. It turns out that, depending on the levels of human capital and technology, research performances could have different trajectories over time. Contingent upon the priority-driven amount of resources devoted to research, university administrators could choose a path among different trajectories, a path that is most compatible with their institutional objectives.

Keywords*:* Simulations of research performances, cross-disciplinary effects, technology.

Araştırma Makalesi

DİSİPLİNLERARASI BAĞLAMLARDA ARAŞTIRMA PERFORMANSI SİMÜLASYONLARI: BİR MODEL VE BİR UYGULAMA

Öz

Bu makalenin amacı, çapraz etkileşimlerin karakterize ettiği disiplinlerarası bağlamlarda, arz ve talebe dayalı bir araştırma performansı modeli kurmak ve performansın seyrini simüle etmektir. Makalede, beşeri sermaye, araştırma teknolojisi ve disiplinlerarası etkileşimlerin dikkate alındığı bir model aracılığıyla, muhtemel performans yörüngeleri incelenmektedir. Beşeri sermayenin düzeyi ve teknolojiye bağlı olarak farklı yörüngelerin mümkün olabileceği ortaya konulmaktadır. Üniversite yönetimleri, değişik performans yörüngeleri arasında, hedeflerine uygun seçimi, araştırmaya öncelikler doğrultusunda tahsis edilmiş kaynakları kullanarak, yapabilirler.

Anahtar Kelimeler: Araştırma performansı simülasyonları, alanlar-arası çapraz etkiler, teknoloji.

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1. INTRODUCTION

Research productivity, which is one of the key indicators of the performance of the universities in modern times, has been an active area of research in the last thirty years. Among the works exploring different dimensions of the issues associated with academic research in particular and universities in general are Abdullah, Jaafar and Taib (2013), Abramo, Cicero & D’Angelo (2012), Abramo, D’Angelo & Di Costa (2014), Adams & Clemmons (2011), Barlas & Diker (2000), Barlas, Diker, Polat (1997), Dundar & Lewis (1995), Fedderke and Luiz (2008), Grayson (2004), Ivanov, Markusova & Mindeli (2016), Jaffe (1989), Kara (2011, 2013a, 2013b, 2014), Kodama, Watatani &Sengoku (2013), Munoz (2016), Millers, Moffettt, McAdam & Brennan (2013), Neri & Rodgers (2013), Pastor & Serrano (2016), Singell and Tang (2013), Spencer (2001), and Walton, Tornatzky & Eveland (1986).

Topics/issues covered in the literature, which constitute a rich spectrum, include, but are not limited to, the determinants of the research output of universities (Pastor & Serrano (2016)), the system-theoretic analysis of the higher educational processes (Barlas & Diker (2000), Barlas, Diker, Polat (1997) and Kara (2011, 2013a, 2013b, 2014)), research efficiency-related issues associated with higher education institutions (Munoz (2016)), the role of human capital in the development of institutions (Fedderke and Luiz (2008)), government investments in relation to the publishing activity of higher educational institutions (Ivanov, Markusova & Mindeli (2016), the effect of human capital on job outcomes (Grayson (2004)), returns to scope of research fields (Abramo, D’Angelo & Di Costa (2014), the ranking of human capital indicators (Abdullah, Jaafar and Taib (2013)), size effects in higher education research productivity (Abramo, Cicero & D’Angelo (2012), the relation between human capital and leadership in universities (Singell and Tang (2013)), the departmental productivity in the context of the issues of economies of scale and scope (Dundar & Lewis (1995)), the relevance of university-based scientific research to private high-technology firms (Spencer (2001)), interdisciplinary issues (Kodama, Watatani & Sengoku (2013), Adams & Clemmons (20111)), real effects of academic research (Jaffe (1989)), Human capital externalities (Neri & Rodgers (2013)), topics involving research management at the university departments (Walton, Tornatzky & Eveland (1986)) and issues of intellectual capital (Miller, Moffett, McAdam & Brennan (2013)).

A comprehensive inquiry into the research performance patterns and practices may reveal some of the characteristics of the complex dynamics governing the research productivity in modern universities. Such an inquiry may take various theoretical and empirical directions and forms, one of which would be a simulation-based theory building, which we will exemplify in this paper. The particular method we choose facilitates the analysis of the intricate cause-and-effect relations behind the research performances.

To contribute to the relatively under-explored dimensions of this area, we will construct a model of research performance, based on a demand-and-supply set-up, in a cross-disciplinary context and simulate the trajectory of research performances. We pay particular attention to the effects of human capital and research technology.

The second section of the paper will develop the model. The third section presents the simulations. Concluding remarks follow in the final section.

2. THE MODEL[2]

Consider a representative institution, such as a university that engages in research in various fields. For the purpose of simplicity, we will consider two related fields/subjects, denoted by 1 and 2. The quantity demanded for the research service in a field 1 at time t (QD_{1t}) depends on the level of research performance for the service 1 at time t (y_{1t}), the relative price of the research service 1 at time t (P_{1t}), the level of human capital associated with service 1 at time t (HK_{1t}), and the level of technology associated with the service 1 at time t (T_{1t}),

i.e., $$QD_{1t} = g^{D_1}\left(y_{1t}, P_{1t}, HK_{1t}, T_{1t}\right)$$

which is a "peculiar" demand function for the research service 1. $P_{1t} \in (0,\infty)$, $HK_{1t} \in (0,\infty)$. By construction, observable y_{1t}, y_{2t} ,T_{1t} take on short-run values between 0 and 7, i.e., $y_{1t} \in (0,7]$, $y_{2t} \in (0,7]$, and $T_{1t} \in (0,7]$. Values exceeding 7 are considered unusually high and achievable in the long run. $QD^{T}_{1t} \in (0,\infty)$.

Let QS_{1t} denote the quantity supplied for the research service 1 at time t, which is a function of the level of research performance for the service 1 at time t (y_{1t}), the level of research performance for the service 2 at time t (y_{2t}), the relative price of the service 1 at time t (P_{1t}), the level of technology associated with the service 1 at time t (T_{1t}), and the level of technology associated with the service 2 at time t (T_{2t}),

i.e., $QS_{1t} = \alpha o + \alpha_1 y_{1t} + \alpha_2 P_{1t} + \alpha 3\ HK_{1t} + \alpha 4 T_{1t} + u_{lt}$, $QS_{1t} \in (0,\infty)$

We will assume that the demand and supply functions for research are of the following forms:

$$QD_{1t} = \alpha o + \alpha_1 y_{1t} + \alpha_2 P_{1t} + \alpha 3\ HK_{1t} + \alpha 4 T_{1t} + u_{lt} ,$$

where $T_{1t} = T_{10}(1 + a1 + z1t)^t$,

and

$$QS_{1t} = \beta_0 + \beta_1 y_{1t} + \beta_2 P_{2t} b + \beta_3\ P_{1t} + \beta_4 HK_{1t} + \beta_5 T_{1t}{}^{c} + \beta_6 T_{2t}{}^{0.5} + v_{1t}$$

where $T_{2t} = T_{20}(1 + a2 + z2t)^t$.

z_{1t}, z_{2t}, u_{1t} and v_{1t} are normally distributed white noise stochastic terms with zero means and constant variances $\sigma_{z1}{}^2$, $\sigma_{z2}{}^2$, $\sigma_{u1}{}^2$ and $\sigma_{v1}{}^2$ respectively.

[2] The model developed here benefits, in part, from Kara (2014).

To model the trajectory of research performance for service 1 over time, the movement over time of research performance for service 1 will be assumed to be proportional to the excess demand for performance,

i.e., $y_{1t+1} - y_{1t} = k(QD_{1t} - QS_{1t})$,

where *k* is the coefficient of adjustment.

This is nothing but a dynamic adjustment equation for the research performance for service 1. Substituting the expressions for QD_{1t} and QS_{1t} specified above, setting the initial values of P_{1t}, HK_{1t} , T_{1t} , T_{2t} to their average values $P_{1t}{}^{avr}$, $HK_{1t}{}^{avr}$, $T_{1t}{}^{avr}$, *and* $T_{2t}{}^{avr}$ and rearranging the terms in the equation, we get,

$$y_{1t+1} + (-1 - k(\alpha_1 - \beta_1)) - y_{1t} = k(\alpha_0 - \beta_0 - \beta_2 y_{2t}{}^{b} + (\alpha_2 - \beta_3)P_{1t}{}^{avr} + (\alpha_3 - \beta_4)HK_{1t}{}^{avr} + \alpha_4 T_{1t}{}^{avr} - \beta_5 T_{1t}{}^{avr} - \beta_6 T_{2t}{}^{0.5avr} + u_{1t} - v_{1t})$$

which is one of the stochastic difference equations that we will employ in the simulations in Section III.

The quantity demanded for the research service in a field 2 at time t (QD_{2t}) depends on the level of research performance for the service 2 at time t (y_{2t}), the relative price of the research service 2 at time t (P_{2t}), the level of human capital associated with service 2 at time t (HK_{2t}), and the level of technology associated with the service 2 at time t (T_{2t}),

i.e., $QD_{2t} = g^{D2}(y_{2t}, P_{2t}, HK_{2t}, T_{2t})$,

which is a "peculiar" demand function for the research service 2. $P_{2t} \in (0,\infty)$, $HK_{2t} \in (0,\infty)$. By construction, observable T_{2t} takes on short-run values between 0 and 7, i.e., $T_{2t} \in (0,7]$. Values exceeding 7 are considered unusually high and achievable in the long run. $QD^{T}{}_{2t} \in (0,\infty)$.

Let QS_{2t} denote the quantity supplied for the research service 2 at time t, which is a function of the level of research performance for the service 2 at time t (y_{2t}), the relative price of the service 2 at time t (P_{2t}), the level of human capital associated with service 2 at time t (HK_{2t}), and the level of technology associated with the service 2 at time t (T_{2t}),

i.e., $QS_{2t} = g^{S1}(y_{2t}, P_{2t}, HK_{2t}, T_{2t})$, $QS_{2t} \in (0,\infty)$.

We will assume that the demand and supply functions for 2 are of the following forms:

$$QD_{2t} = \theta_0 + \theta_1 . y_{2t} + \theta_2 . P_{2t} + \theta_3 HK_{2t} + \theta_4 T_{2t^d} + u_{2t}$$

and

$$QS_{2t} = \delta_0 +_1 \delta . y_{2t} + \delta_2 . P_{2t} + \delta_3 HK_{2t} + \delta_4 T_{2t^e} + v_{2t}$$

where u_{2t} and v_{2t} are independent normally distributed white noise stochastic terms with zero means and constant variances σ_{u2}^2 and σ_{v2}^2 respectively.

To model the trajectory of research performance for service 2 over time, we will assume that the movement over time of research performance is proportional to the associated excess demand,

i.e., $y_{2t+1} - y_{2t} = k*(QD_{2t} - QS_{2t})$,

where $k*$ is the coefficient of adjustment.

This is of course a dynamic adjustment equation for the research performance for service 2. Substituting the expressions for QD_{2t} and QS_{2t} specified above, setting the initial values of P_{2t}, HK_{2t}, T_{2t} to their average values P_{2t}^{avr}, HK_{1t}^{avr} *and* T_{2t}^{avr} and rearranging the terms in the equation, we get,

$$y_{2t+1}\left(-1-k*\left(\theta_1-\delta_1\right)\right)=k*\begin{pmatrix}\theta_0-\delta_0+(\theta_2-\delta_2)P_{2t}^{avr}+\\(\theta_3-\delta_3)HK_{2t}^{avr}+Q_4T_{2t}^{davr}-\delta_4)T_{2t}^{eavr}+u_{2t}-v_{2t}\end{pmatrix}$$

which is the stochastic difference equation describing the movement of the research performance for service 2 over time.

The two stochastic difference equations we have derived above will serve as a basis for the simulations that we will undertake in the following section.

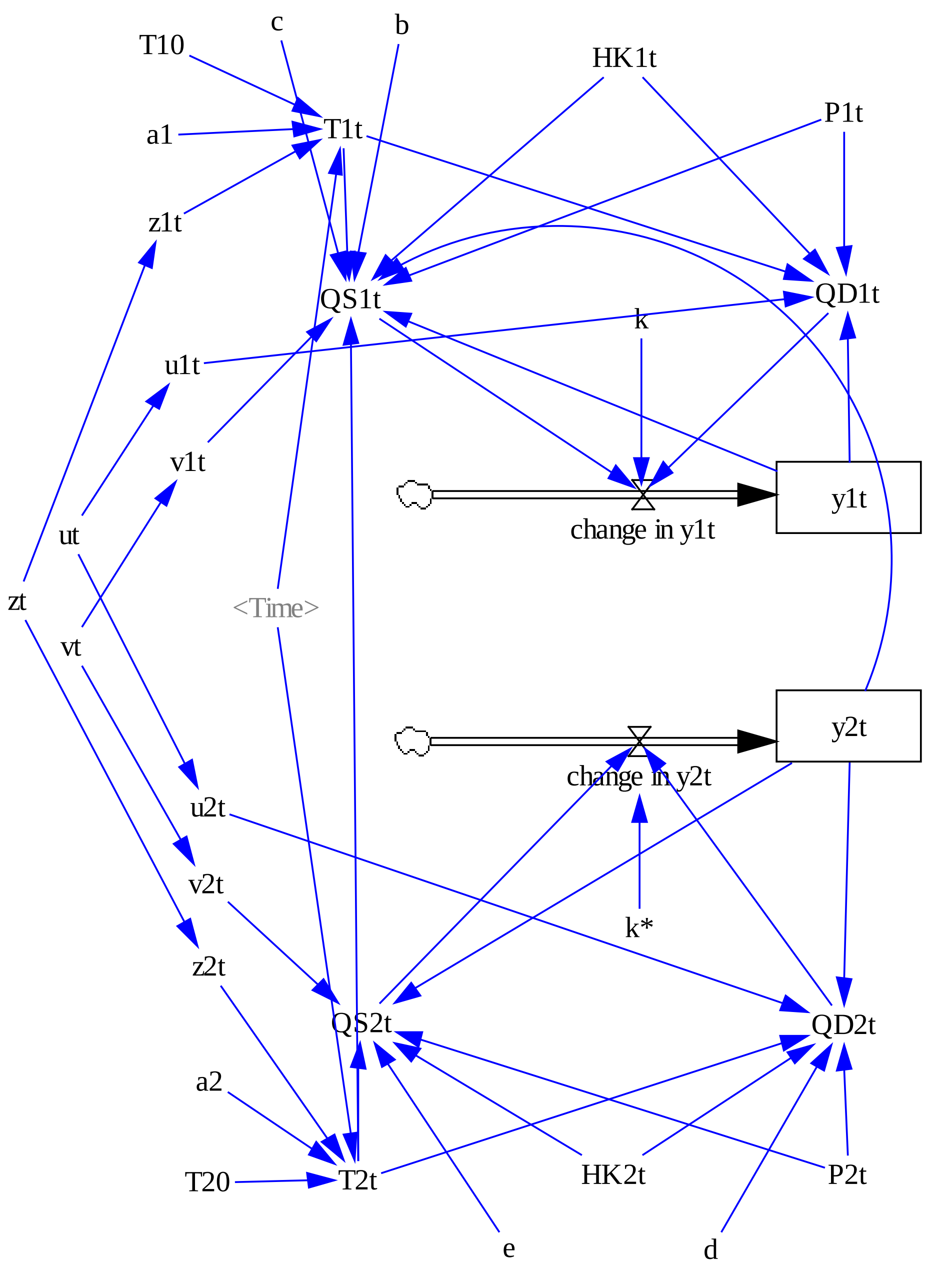
3. SIMULATIONS[3]

We will make use of system dynamics method to carry out simulations for research performance. The method takes stocks, flows and auxiliary variables as the building blocks and requires that multiple causal connections among the variables be specified mostly in the form of feedback relations or structures. In our model we take the designated research performances as the stocks, the change of which are described as the flow variables. Other variables are of the auxiliary type playing key roles in specifying the feedback relations within the system.

The simulation diagram describing the stochastic-equation-based causal connections and feedback-relations within the system is as follows:

[3] Programs ranging from NET LOGO to VENSIM could be used for simulation purposes. We have used VENSIM. MATLAB could be used as well. The description of the system dynamic processes in this section is similar to the one in Kara (2016).

Figure 1: Simulation Diagram



Research performances evolve over time through demand and supply and the adjustment dynamic specified in the model.

For simulation purposes, let: α_0 = 1, α_1 = 0.9, α_2 =-0.7, α_3 = 0.7, α_4 = 0.6, β_0 = 0.9, β_1 = 0.5, β_2 =0.3, β_3 = 0.4, β_4 = 0.4, β_5 = 0.4, β_6 = 0.3, k = 0.1, P_{1t}^{avr} = 1, a_1 = 0.03, HK_{1t}^{avr} = 2.5 and T_{10} = 2.

The initial y_{1t} = 2, the initial y_{2t} = 1.8. θ_0 = 1, θ_1 = 0.8, θ_2 =-0.5, θ_3 = 0.4, θ_4 = 0.25, δ_0 = 0.8, δ_1 = 0.55, δ_2 =0.3, δ_3 = 0.25, δ_4 = 0.1, k* = 0.1, a_2= 0.04. P_{2t}^{avr} = 1.1, HK_{2t}^{avr} = 2.5 and T_{20} = 2. u_{1t} =0.6u_t, v_{1t} =0.4v_t, u_{2t} =0.5u_t, v_{2t} =0.5v_t, and z_{1t} =0.001z_t, z_{2t} =0.001z_t, z_t is a random variable that takes a value between zero and one. u_t and v_t are random variables with zero mean and standard deviation of 0.1. The simulated stochastic trajectories of y_{1t}, y_{2t} and y_{1t}-y_{2t} relations are as follows: Figure 2 and 3 illustrate the research performances with the initial (low) and increased (high) human capital. Figure 4 display the cross-evolution of the performances in question.

Figure 2: y_{1t} with the initial (low) and increased (high) human capital

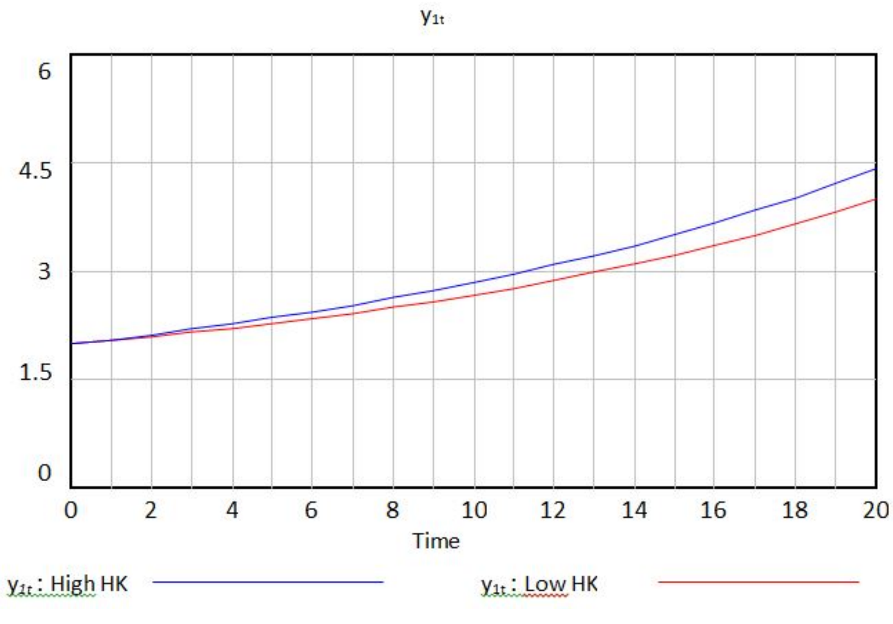
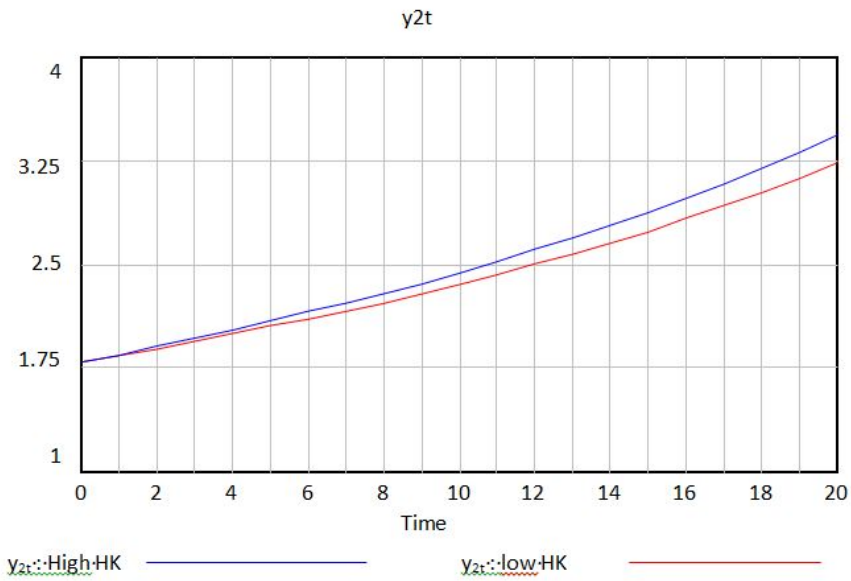
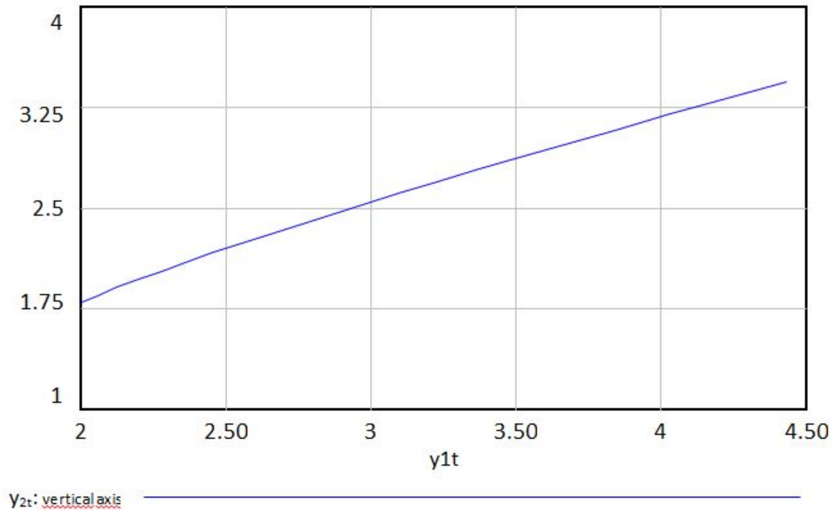


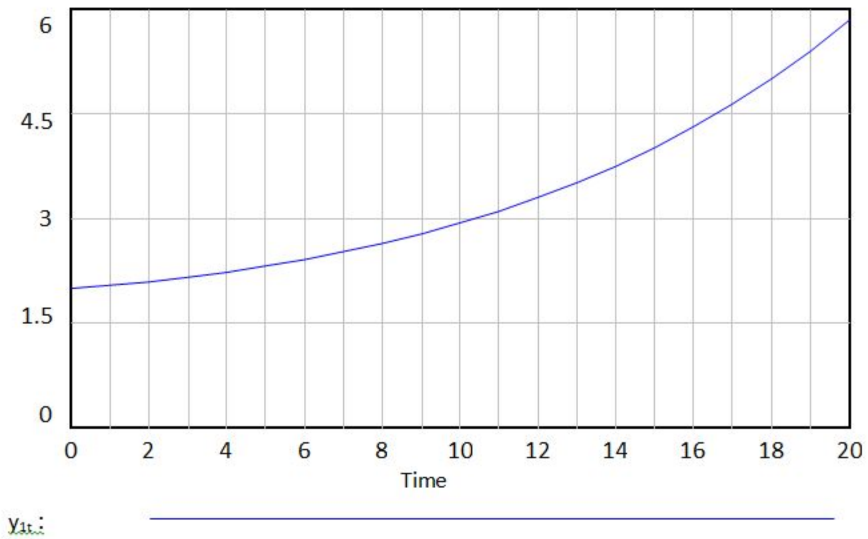
Figure 3: y_{2t} with low and high human capital





Similarly, we can simulate the trajectory of research performances with an improved research technology. For instance, an increase in the technological growth parameters (a_1 and a_2) would considerably improve the research performance y_{1t} , as illustrated in Figure 5 below.

Figure 5: y_{1t} with rapidly evolving technology (with a_1=a_2=0.07)



Clearly there are, in the model, many deterministic and stochastic factors influencing the trajectories of the variables. Their presence leads to stochastic fluctuations around the deterministic trends of the variables in question. In the simulation set-up, stochastic factors are kept small in magnitude; graphs do not discernably reflect their effects. On the other hand, the steepness of the graphs clearly depends on the values of a variety of parameters representing, for instance, the technological growth or the degree of complementarity between subjects.

Graphs display a number of features of the performance trajectories. First increases in the human capital employed in research lead to upward shifts in the trajectories of research performances (Figure 2 and 3). Second, changes in the research performance for subject 2 are positively associated with the changes in the research performance for subject 1, demonstrating, within the causal structure of the model, the positive cross-influence of y_{2t} on y_{1t} (Figure 4). Third, technological growth, as illustrated in Figure 5, positively influences the relevant research performance.

4. CONCLUDING REMARKS

Results above exemplify the possibility of improvement in research performance due to improved human capital and intra-or-cross-disciplinary research technology. There are, of course, many other sources of improvement, and the extraordinary richness in sources is mostly in the details of performance-generating processes. For instance, the intricate ways one research area (research in one discipline) depends on another could contain new possibilities for performance improvements. A striking example would be the dependence of economics on computational science/computational methods. With improved computational methods (and hence an improved research technology), the extent and depth of economic research has gone well beyond what could have been achieved in the past. With the introduction of these methods, the dimensions, reach and complexity associated with market analysis have improved quite dramatically in the last quarter of a century.

With proper investments in the research technology and human capital, different evolutionary trajectories/paths for research could be obtained. University administrators could optimally choose the path that is most conducive to their overall objectives.

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