Economic Modelling xxx (2017) 1–16

Contents lists available at ScienceDirect

Economic Modelling

journal homepage: https://www.journals.elsevier.com/economic-modelling

Co-evolutionary growth: A system dynamics model

Fulvio Castellacci

TIK Centre, University of Oslo, Postboks 1108, Blindern, 0317 Oslo, Norway

ARTICLE INFO

JEL:
C6
H5
O1
O3
O4

Keywords:
Co-evolution
System dynamics
Simulation analysis
Multiple equilibria
Nonlinear growth

ABSTRACT

The paper presents a new modelling approach for the study of co-evolutionary economic growth. The system dynamics model studies the interactions between four main dimensions: physical capital, R&D and innovation, human capital, and population dynamics. These factors interact with each other in a complex manner, leading to co-evolutionary growth of the economic system. The model generates nonlinearities and multiple growth trajectories, determined by countries' structural characteristics and policy parameters. Developing economies that are able to activate and support synergies among their main growth engines can achieve a faster catch up process and more sustained income per capita level in the long-run than countries characterized by weak co-evolutionary dynamics.

1. Introduction

Economic development is a multidimensional process: several factors contribute to explain economic growth and transformations in the long-run. Most scholars interested in growth theory would arguably agree with this statement. However, the field of economic growth has so far developed in a fragmented way, in which different approaches and schools of thought have pointed out the relevance of different growth engines, each focusing on one dimension and often neglecting the others.

Typical examples are the influential model strands focusing on physical capital accumulation (Solow, 1956), human capital (Lucas, 1988; Benhabib and Spiegel, 1994), and R&D-driven growth (Romer, 1990; Aghion and Howitt, 1992). The reason for this is clear enough: by focusing on one or few important factors and neglecting the others, a growth model can be analytically tractable, and so it is able to provide a thorough analysis of its steady-state properties. Each new growth model describes a subset of relevant mechanisms that were previously unknown in the literature, thus pushing forward the scientific knowledge in this field.

A drawback of this research strategy, though, is that it neglects the study of the interactions among the various growth engines highlighted by different modelling strands. Economic growth is a co-evolutionary process: several factors co-evolve over time in a complex manner. How can we model such a complex co-evolutionary process?

Some multiple equilibria models have studied the interactions among different growth factors. Notable examples are multiple equilibria models based on the dynamic interaction between human capital accumulation and technological change (Galor and Moav, 2000; Howitt, 2000; Howitt and Mayer-Foulkes, 2005), new product developments and industrial structure (Kelly, 2001; Hausman and Hidalgo, 2011), population and human capital dynamics (Galor and Weil, 2000; Galor, 2005) or social capital and trust (Growieca and Growieca, 2014). In a nutshell, these models show how dynamic feedback effects among two or more variables can generate rapid growth for some developing economies and sluggish performance for others, and so explain the existence of multiple steady states and convergence clubs.

Related to this strand of research, this paper presents a new modelling approach for the study of co-evolutionary economic growth. We build up a comprehensive growth model that, instead of focusing on one or few growth engines, considers together some of the major growth factors previously studied in growth theory: physical capital accumulation, R&D and innovation, human capital, and population dynamics. The model studies the complex interactions and co-evolutionary process that link these factors together.

In order to simultaneously take into account these factors and their interactions, we make use of a *system dynamics modelling* approach (Forrester, 1961; Sterman, 2002; Booth Sweeney and Meadows, 2010). System dynamics (SD) models are well-suited to study co-evolutionary

E-mail address: fulvio.castellacci@tik.uio.no.

https://doi.org/10.1016/j.econmod.2017.11.010
Received 11 March 2017; Received in revised form 1 October 2017; Accepted 12 November 2017
Available online xxxx

processes, since they focus on the complex set of feedback mechanisms – or *causal loops* – that describe the interaction between the relevant variables in the system (Barlas, 1996). Emphasizing the importance of feedback effects in dynamic and complex systems, SD modelling represents an appealing approach to investigate co-evolutionary economic growth, which is indeed driven by the interactions between several related factors such as capital accumulation, R&D and innovation, and population dynamics.

Specifically, the model that we present in this paper aims at representing the evolution of national economies as driven by the interactions among four distinct growth engines: (1) production and physical capital accumulation; (2) R&D and innovative activities; (3) education and human capital formation; (4) health and population dynamics. The key novelty of this exercise is that, while most previous studies in this field have typically focused on one of these dimensions at a time and neglected the others, our SD model considers them simultaneously and studies the dynamic interactions among them. The simulation analysis shows that the model determines multiple steady states depending on countries' structural characteristics and their set of policy parameters. Specifically, we simulate three distinct growth trajectories: a *growth disaster* country, which does not experience any visible improvement in its income per capita level over time; a *middle-income trapped* economy, which grows steadily and slowly, but its transitional dynamics process is long and does not enable to catch up with advanced countries at the frontier; and a *growth miracle* country, which grows rapidly following a nonlinear trend and completes its catch up process by reaching its steady state level in a relatively short period.

The contribution of this work is to propose SD modelling as a brand new approach to study co-evolutionary economic growth. The main advantage of this approach is its comprehensiveness, i.e. its endeavor to study economic development as a complex process driven by the co-evolution of a multiplicity of variables (Castellacci and Natera, 2013).

The paper is organized as follows. Section 2 briefly summarizes extant literature on co-evolutionary growth, and it presents the main ideas and building blocks of the SD modelling approach. Sections 3.1–3.4 present the four main sections of the model: (1) production sector and physical capital accumulation; (2) R&D sector and innovation; (3) education sector and human capital; (4) health sector and population dynamics. Section 3.5 presents an overview of the model and a summary of the main co-evolutionary mechanisms. Section 4 discusses the simulation results and long-run properties of the model. Section 5 concludes by discussing the main advantages and possible limitations of the use of system dynamics modelling in growth theory.

2. Background and approach

2.1. Co-evolutionary growth

While the concept of co-evolution has been studied in biology and natural sciences for a long time already, its use in the social sciences is relatively recent, and its application in economics is still rather limited. In general terms, co-evolutionary growth arises when the dynamics of a system is driven by the growth and mutual interactions between two or more variables (Winder et al., 2005). The idea of co-evolution has in the last few years been used to investigate a variety of different topics broadly related to the fields of economics, business and management studies.

For instance, there are several relevant works that illustrate the use of this approach within the field of innovation and industrial dynamics. Geels (2006) is a seminal study of the emergence and diffusion of new technological paradigms and industries. Windrum and Birchenhall (1998) studied a model of dominant designs and the emergence of market niches. Hacklin et al. (2009) and Robinson (2009) investigated co-evolutionary processes that explain the emergence and diffusion of ICTS and nanotechnologies, respectively. Ríos-Núñez et al. (2013) studied co-evolutionary changes in Spanish livestock; and Quitzow (2015) focused on the case of solar photovoltaics in China and Germany.

Other applications of co-evolutionary theory have focused on the aggregate level of national economies, and studied national systems of innovation and economic development (Sotarauta and Srinivas, 2006). Tsai et al. (2009) pointed out the role of business incubation and national innovation systems in Taiwan. Wong (2009) studied the co-evolution of industrial policies and national innovation systems in Southeast Asian economies. Castellacci and Natera (2013) presented a panel cointegration study of the co-evolution between innovative capability and absorptive capacity in national innovation systems. More recently, García-Cabrera and Durán-Herrera (2016) studied the interplay between institutions and multinational enterprises.

Other works have applied the concept of co-evolutionary growth to study firm-level and organizational dynamics. Reid and Smith (2009) studied information system dynamics in small entrepreneurial firms. Abatecola (2012) focused on corporate crises and suggested to explain them as the co-evolution of managerial and environmental factors. Hynes and Wilson (2012) studied the formation of strategic alliances between firms along the industry life cycle. And Luo et al. (2015) presented a microfounded model of knowledge diffusion and social network structure.

2.2. The system dynamics modelling approach

Although the studies noted in the previous section investigate a variety of different topics, what they have in common is the focus on the dynamic and feedback nature of co-evolutionary growth, in which several variables interact with each other driving the growth of the system. The focus on the dynamic and feedback nature of a system is precisely the typical feature of a system dynamics modelling approach (Barlas, 1996).

System dynamics (SD) is a modelling methodology that studies the dynamic interactions and feedback effects among a set of variables that compose a system (Forrester, 1961; Sterman, 2002; Booth Sweeney and Meadows, 2010).[1] Variables are conceptualized as stocks, with inflows and outflows that determine the value of each stock variable at a given time, and information flows that connect the various stock variables together.

A SD model is driven by several feedback mechanisms interlinked with each other. Each feedback mechanism – or *causal loop* – describes the interaction between two (or more) variables in the system. A feedback can lead either to a *reinforcing loop*, in which the dynamics of two variables support each other, or to a *balancing loop*, in which one variable attenuates the growth of the other and brings it back to its equilibrium path. The whole set of causal loops determines the dynamics of the system over time. A typical way to represent and visualize causal loops in SD models is the so-called *causal loop diagram*, which consists of a set of nodes and edges. *Nodes* are the variables composing the system, and *edges* are arrows representing the causal relationships among these variables (Barlas, 1996; Sterman, 2002).

Mathematically, a system dynamics model is represented as a set of ordinary nonlinear integral equations. Since it is typically not possible to obtain mathematically analytical solutions and dynamic equilibrium conditions for this type of system, system dynamics models make use of computer simulations to analyze its dynamic behavior and time trends.

Forrester (1979), Barlas (1996) and Sterman (2002) discuss model validation and analysis in the SD approach. In short, SD model analysis consists of two phases. One is to carry out computer simulations to perform a sensitivity analysis, which is important to understand "why the model behaves the way it does" (Barlas, 1996), and the dynamic outcomes it leads to over time. The second is to carry out simulations to perform a policy analysis, in which the analyst studies the extent to

[1] Recent examples of applications of the SD approach are for instance Castellacci and Hamza's (2015) study of policy strategies for development, and Feng et al.'s (2016) study of water supply and environmental systems.