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Název práce :

Dynamics in the Extended Cass-Koopmans-Ramsey Growth Model

Disertant: Ing. Lukáš Režný

Školitel: prof. Ing. Ladislav Hájek, CSc.

Oponent disertační práce : doc. RNDr. Ing. Ladislav Lukáš, CSc.
ZČU v Plzni, FEK, KEM

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REVIEWER'S REPORT OF THE DOCTORAL THESIS

Dynamics in the Extended Cass-Koopmans-Ramsey Growth Model

submitted by: Ing. Ladislav Režný

By introducing my reviewer's opinion, I note that the author has chosen an interesting and important topic of his doctoral thesis that is concerned with economic growth models amended with energy sector, in particular. The author has divided his thesis into eight chapters and usual supplements, i.e. abstract, lists of figures, tables and abbreviations, his own publications, bibliography, and annex containing code procedures developed. In general, I consider the layout of chapters and their functional and logical connections to be successfully processed. The first and second chapters are short dealing both with topic introduction and purpose and aims of the work. The author's main aim declared is to create a system dynamics model of economic growth which will be able to analyze various crucial effects of fossil fuels consumption upon growth rate itself. Chapter 3 is called Methodology, and it should give a theoretical background for the whole work. It consists from three sub-chapters, in particular, 3.1 "Short note on the general structure of System Dynamics models", 3.2 "Solow-Swan Growth model", and 3.3 "Ramsey-Cass-Koopmans model". However, I was rather disappointed thereof as due to my opinion the themes are poorly processed and elaborated in a very superficial way. Here, I give just few critical comments of mine. In 3.1, page 6, rows 12 and 11 from the bottom, one reads "Mathematically, the process of flows accumulating/de-cumulating in stocks is called integration. The integration process creates all dynamic behaviour in the world …". Well, I might accept it in spite of well-known fact that the main and traditional mathematical instrument used for building growth models in macroeconomics there are ordinary differential equations expressing local balance of economic entities considered. One also knows that differential equations can be recast into integral equations by suitable technical manipulations. Hence, I do think the author should mention this theoretical framework briefly or at least an integral, both definite and indefinite one of a continuous function of time in clear mathematical formulation, in order to elucidate basic entities of system dynamics, stocks and flows, formally. Further, the above mentioned sentences also support a continuous-time concept of system dynamics models. But on the contrary, in 3.1, page 6, rows 6 and 5 from the bottom, one reads "The change of S from t to t+1 is represented by s'", which is rather confusing in notation first, and moreover it boosts a discrete-time concept in opposite to continuous-time one being promoted just a few rows above. In sub-chapter 3.2, page 7, the economic quantities, i.e. capital stock K, labour supply L, and technological progress A, are written in a very loose way as did not specify them to have been functions of time precisely. Page 8, my reserve goes to formulation of Solow-Swan growth model. Core of the model, a single differential equation that models the evolution of the capital stock, in particular per capita, is absolutely missing. Due to my opinion, a symbolic scheme composed from graphical icons cannot substitute clear mathematical formulation of Solow-Swan model available in almost all standard textbooks of macroeconomics. The situation is getting even worse in sub-chapter 3.3. In accordance with the thesis title, the Ramsey-Cass-Koopmans (abbreviated R-C-K) model should be theoretical cornerstone of the whole work.

However, in this sub-chapter and opposite to my expectation, this model is specified loosely in words again. I'm sure that only exact mathematical formulation of the R-C-K model can reveal the correct reason of inability to solve this model within system dynamics framework as it is a dynamic optimization problem and not a descriptive one. As such, it needs to use methods of optimal control, in particular variational methods, dynamic programming technique, or Pontryagin's maximum principle. On the contrary, pure system dynamics framework assumes, but quite in concealed way, models to be formulated as initial value problems for ordinary differential equations. Hence, summarizing whole chapter 3, I get a feeling the thesis title to be at least disputable one, as generally known, the main issue of the R-C-K model is the time-dependent consumption having been determined by maximizing lifetime discounted utility defined over consumption per worker. Whereas citing author's text on page 10, the last paragraph, "In the circumstances of the model developed in the dissertation, it is important for the population to have the opportunity to suddenly change their saving behaviour, ..., when it is necessary to invest more into the capital stock in the energy sector.", it means in particular the time-dependent saving, and consumption subsequently too, becomes an exogenous quantity given a priori.

Next, chapter 4 brings review of literature being thoroughly selected with lot of motivating ideas and published models concerning relations between economic growth and energy consumption mainly. Among others, the pivot role is played by the Dynamic Integrated model of Climate and the Economy (abbreviated DICE), which is also referenced frequently within the thesis. Practically, in all models discussed, there is used and promoted the system dynamics approach uniquely.

Core of the thesis and author's main contributions to the topic are presented within chapters 5 and 6, and the annex, as well. Chapter 5 starts with general description of the author's model which is based upon the Solow-Swan Growth model. Author's original contribution relates rather detailed elaboration of production sector including both effects of energy availability on capital usability in production and also endogenous saving rate, which reacts on total capital amount and availability of energy resources for its operation. The energy sector is decomposed additively into two components, i.e. renewable energy source and non-renewable one, respectively. The model is implemented in the software ISEE systems Stella, ver. 9.1.3. In sub-chapters 3.2, 3.3, and 3.4, there are described subsequently, the user interface and all input data of the model, standard modules, and added ones, all specified by corresponding system dynamics schemes containing typical components, i.e. reservoirs, flow pipes and feed-back loops. Few mathematical expressions and quantities which appear therein are a little bit questionable in their form. In principle, all of them should be time-dependent ones except constants introduced, sure. However, it is not the case, for example on page 48 the production function, and on the next page the investment *I*, just mentioning two of them shortly.

Chapter 6 is focused upon model dynamics entirely. It contains five sub-chapters in total. The first four ones give four different scenarios, denoted A, B, C, and D, respectively, of economic growth, energy sector and investment, in particular, while the fifth one discusses sensitivity analysis for the last scenario D. In whole chapter 6, a general and unifying idea of all examples run with the author's model is the simulation period between years 1965 and 2065. Based upon available data, the model tries to recreate historical development of macroeconomic entities considered within the first half of the simulation period, i.e. till 2015. The forecast of their development within the next fifty years, i.e. till 2065, in particular, there is the main issue of this chapter. All results of dynamic model simulations are presented on 21 figures in total, starting with Fig. 34, and ending with Fig. 54. Well, concluding my impression from chapters 5 and 6, I consider the sub-chapter 6.5 to be the most interesting and important one in the thesis at all. It summarizes the sensitivity analysis performed with scenario D which assumes a rate of technological factor to be an increasing but concave function till 2065 and reaching a saturated value thereafter. In particular, Renewable Energy Capital Lifetime, Load Factor, Price Reduction per Total Capacity Doubling, and Renewables Price, there are parameters selected and properly varied to get sensitivity analysis of simulated forecasts. Being focused on energy returned on energy invested ratio (abbreviated EROEI), the author has selected these parameters intentionally. In total, there are five sets of particular values for these parameters which are given in Tab. 16, on the page 75. In general, the first three parameters are decreasing, while the fourth one, i.e. the Renewables Price, is increasing. Sure, the particular parameter values can be submitted to discussion, but the results obtained by numerical experiments show an ability to analyze any similar value combinations by author's model effectively.

The last two chapters, bring both a brief discussion of main thesis results and conclusions drawn thereof. Finally, the thesis contains also a list of author's works published yet, list of references, and the annex containing at first, source lists of modules of the model proposed by author and given in system dynamics software ISEE Stella, and at second, model calibration for the few basic variables.

The English used within the thesis fluctuates between the American style, e.g. "labor" on page 7, row 7 from the bottom, and sometimes the British one, e.g. "behaviour" on page 7, row 2 from the top. However in general, a language level of the thesis is quite satisfactory, which is probably also influenced by fact that all of 68 papers and books referenced therein are written in English exclusively. Albeit having a minor comment thereon, the correct author's name of the sources [23] and [55], see pages 85 and 88, respectively, is T.S. Fiddaman. Though, his name is misprinted on page 22, row 2 from the bottom, and on page 88, the source [55], as well, while on the page 23, Fig.10, which refers to the source [55] actually, his name is typed correctly.

Regarding a formal form of the thesis, I can conclude, but except general convention of writing mathematical symbols, variables, expressions and equations, it is satisfactory, too. On the opposite, correct writing of mathematics is a weak point. For an illustration purpose only, I refer just following one.

Page 26, the last paragraph at the bottom: "... production function is Y=f(K,L,U), ..." should be "... production function is $Y=f(K,L,U)$, ...", i.e. written in italics, as well as the all variables should be Y, K, L, and U in italics, too, and if having been denoted with majusculies they should be used in adjacent analytic expression specifying a particular form of production function in the same way precisely. The minusculies therein are incorrect and misleading, moreover, the quantities a and b are not defined at all.

Questions and ideas for discussion during the thesis defense

1. In order to fill a theoretical gap, formulate and discuss the Solow-Swan growth model and Ramsey-Cass-Koopmans one in mathematical forms which are available in almost all classical textbooks of macroeconomics, traditionally.
2. Discuss weird local saw-like time-dependent developments of total investments and energy sector investments presented in Fig-s. 42, 43, 48, and 52, and explain correctly scales and measure units of total product on vertical axes therein.

Statement on the proposal to award a Ph.D. degree

I do recommend the work *Dynamics in the Extended Cass-Koopmans-Ramsey Growth Model* to the defense at the relevant examination board for the doctor dissertation defense at the Faculty of Informatics and Management, University of Hradec Králové.

At the same time, I also recommend that in case of a successful defense, Mr. **Ing. Lukáš Režný** is awarded subsequently the doctor's degree in the field of **Information and Knowledge Management**.

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In Pilsen 2017-11-20

doc. RNDr. Ing. Ladislav Lukáš, CSc.
University of West Bohemia in Pilsen,
Faculty of economics,
Department of economics and quantitative methods