University of Hradec Králové

Faculty of Informatics and Management

Department of Economics

Simple DICE Model

Bachelor Thesis

Author: Roman Bakhta
Study Branch: Financial Management

Thesis Supervisor: Ing. Lukáš Režný, Ph.D.

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I hereby declare that I carried out this bachelor thesis independently, and only with the cited sources, literature, and other professional sources.

Hradec Králové 09.11.2022 Roman Bakhta

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Mum, dad, Diana – I owe you a lot, as none of this would be possible without you.
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Zuzana – your warmth helped me so much.

Annotation

This paper aims to explore climate-economy interaction through the dynamic modelling in IAMs (Integrated Assessment Models), William Nordhaus' DICE (The Dynamic Integrated Climate-Economy model) in particular. As DICE model is based on neoclassical model of economic growth, Solow-Swan economy growth model is profoundly described in the thesis. An essential part of the theory is to acquaint the reader with the system dynamics, which is a key concept on which the whole modelling in IAMs is based. As DICE model is rather controversial, the reader is also presented with the history and description of the model and the reception of it in the scientific world – including the criticism. Simple DICE model was created in STELLA modelling software, the history and utilisation of which is also described in the paper. The practical part of the thesis acquaints the reader with individual components of the Simple DICE model, compares climate and non-climate model and analyses the results.

Keywords:

environment-economy systems, IAM, system dynamics, DICE, climate change

Anotace

Tato práce se zabývá zkoumáním klimaticko-ekonomické interakce, a to pomocí dynamického modelování v IHM (Integrovaných hodnotících modelech), konkrétně v DICE modelu (Dynamický integrovaný klimaticko-ekonomický model) Williama Nordhause. Protože DICE model je založen na neoklasickém modelu ekonomického růstu, Solow-Swanův model ekonomického růstu je popsán v této práci. Značná pozornost v teoretické části práce je věnována seznámení čtenáře se systémovou dynamikou, která je klíčovým konceptem, na kterém je založeno modelování v IHM. DICE model je kontroverzní, proto čtenář je také seznámen s historií vývoje a detailním popisem modelu a tím, jak byl DICE model přijat vědeckým světem – včetně kritiky. Jednoduchý DICE model byl vytvořen v modelovacím softwaru STELLA, jehož historie je také popsána v této práce. Praktická část práce seznamuje čtenáře s jednotlivými komponenty Jednoduchého DICE modelu, porovnává klimatický a neklimatkicý model a analyzuje výsledky.

Klíčová slova:

ekonomicko-klimatické systémy, IAM, systémová dynamika, DICE model, klimatická změna

Content

List of figures

List of tables

1 Introduction

Climate change is the quintessential dynamic problem, that will have impact on all areas of human life – including economy. Understanding the interaction of climate and economy is thus vitally important. Studies focused on the interrelationship of economic systems and environment have been a subject of interest for many decades. Yet even though the problem only deepens and already has and will continue to have a serious impact on the world and its economy, little attention is dedicated to the problem at economy lessons for undergraduates, on whose generation climate change will have even a greater impact.
The subject of the thesis is to introduce a reader to this issue through acquainting a reader with dynamics – modelling technique that enables us to modify and elaborate existing economic models. This thesis does so through building of a simplified DICE model in STELLA modeling tool and describes the main principles of the model's functionality so that it can be later used by undergraduate students to learn the basics of economy-environment interaction, dynamics, model building and grasp the main principles of the DICE model.

2 Climate change

2.1. Causes and impacts

Climate change is a serious global threat, which will affect the basic elements of life for people around the world – access to water, food production, health, and the environment. Hundreds of millions of people could suffer hunger, water shortages and coastal flooding as the world warms.

Climate change is caused by the greenhouse gas (GHG). The scientific consensus is clearly expressed in the reports of the Intergovernmental Panel on Climate Change (IPCC). In its most recent report, IPCC states unequivocally that the Earth's climate is being affected by human activities:

> *"Observed increases in well-mixed greenhouse gas (GHG) concentrations since around 1750 are unequivocally caused by human activities".*
>
> *"Human influence is very likely the main driver of the global retreat of glaciers since the 1990s and the decrease in Arctic Sea ice area between 1979–1988 and 2010–2019".*
>
> *"It is virtually certain that the global upper ocean (0–700 m) has warmed since the 1970s and extremely likely that human influence is the main driver. It is virtually certain that human-caused CO_2 emissions are the main driver of current global acidification of the surface open ocean. There is high confidence that oxygen levels have dropped in many upper ocean regions since the mid-20th century, and medium confidence that human influence contributed to this drop".* (IPCC Working Group I, 2021).

Warming will have many severe impacts, often mediated through water:

• Melting glaciers will initially increase flood risk and then strongly reduce water supplies, eventually threatening one-sixth of the world's population, predominantly in the Indian sub-continent, parts of China, and the Andes in South America.

• Declining crop yields, especially in Africa, could leave hundreds of millions without the ability to produce or purchase sufficient food. At mid to high latitudes, crop yields may increase for moderate temperature rises (2 - 3°C), but then decline with greater amounts of warming. At 4°C and above, global food production is likely to be seriously affected.

• In higher latitudes, cold-related deaths will decrease. But climate change will increase worldwide deaths from malnutrition and heat stress. Vector-borne diseases such as malaria and dengue fever could become more widespread if effective control measures are not in place.

• Rising sea levels will result in tens to hundreds of millions more people flooded each year with warming of 3 or 4°C. There will be serious risks and increasing pressures for coastal protection in Southeast Asia (Bangladesh and Vietnam), small islands in the Caribbean and the Pacific, and large coastal cities, such as Tokyo, New York, Cairo, and London. According to one estimate, by the middle of the century, 200 million people may become permanently displaced due to rising sea levels, heavier floods, and more intense droughts.

• Ecosystems will be particularly vulnerable to climate change, with around 15 - 40% of species potentially facing extinction after only 2°C of warming. And ocean acidification, a direct result of rising carbon dioxide levels, will have major effects on marine ecosystems, with possible adverse consequences on fish stocks (Stern, 2007).

2.2. Relationship to economic growth

The current generation benefits from using fossil fuels but does not internalize these external costs. As a result, climate change is what economists call a negative externality (Tsigaris and Wood, 2016). Emissions have been, and continue to be, driven by economic growth; yet stabilization of greenhouse-gas concentrations in the atmosphere is feasible and consistent with continued growth (Stern, 2007).

Covert et al., (2016) examine historical data on fossil fuel production and consumption and conclude that neither supply (e.g., Peak Oil) nor demand (e.g., development of low-carbon technologies) factors will sufficiently reduce GHG emissions. Without government intervention, humans will overproduce GHG emissions.

The climate change problem is further complicated as being a global externality rather than a local one. Even though each nation emits a different amount of greenhouse gases, the marginal impact of a tone of GHG is independent of where it is emitted (Tsigaris and Wood, 2016; Stern, 2007).

3 Neoclassical model of economic growth

3.1. Solow-Swan Neoclassical Growth Model

To understand how capital accumulation and technological change affect the economy, we must understand the neoclassical model of economic growth. This approach was pioneered independently by Robert Solow and Trevor Swan. The neoclassical growth model serves as the basic tool for understanding the growth process in advanced countries and has been applied in empirical studies of the sources of economic growth.

The neoclassical growth model describes an economy in which a single homogenous output is produced by two types of inputs – capital and labor, the latter is assumed to be a given. In addition, we assume that the economy is competitive and always operates at full employment, so we can analyze the growth of potential output.

The major new ingredients in the neoclassical growth model are capital and technological change. For the moment, assume that technology remains constant. Capital consists of durable produced goods that are used to make other goods. Capital goods that are used to make other goods. Capital goods include structures like factories and houses, equipment like computers and machine tools, and inventories of finished goods in process.
For convenience, we will assume that there is a single kind of capital good (call it K). We then measure the aggregate stock of capital as the total quantity of capital goods. In our real-world calculations, we approximate the universal capital goods (i.e., the constant-dollar value of equipment, structures, and inventories). If L is the number of workers, then (K/L) is equal to the quantity of capital per worker, on the capital-labor ratio. We can write our aggregate production function for the neoclassical growth model without technological change as

$$Q = F(K, L) \tag{1}$$

Turning now to the economic-growth process, economists stress the need for capital deepening, which is the process by which the quantity of capital per worker increases over time. Examples of capital deepening include the multiplication of farm machinery and irrigation systems in farming, of railroads and highways in transportation, and of the increasing use of computers in banking. These are all examples of how the economy invests in capital goods, increasing the amount of capital per worker. As a result, the output per worker has grown enormously in farming, transportation, and banking.

What happens to the return on capital in the process of capital deepening? For a given state of technology, a rapid rate of investment in plant and equipment tends to depress the rate of return on capital. This occurs because the most worthwhile investment projects get undertaken first, after which later investments become less and less valuable. Once a full railroad network or telephone system has been constructed, new investments will branch into more sparsely populated regions or duplicate existing lines. The rates of return on these later investments will be lower than the high returns on the first lines between densely populated regions.

In addition, the wage rate paid to workers will tend to rise as capital deepening takes place. Why? Each worker has more capital to work with and his or her marginal product therefore rises. As a result, the competitive wage rate rises along with the marginal product of labor. We can summarize the impact of capital deepening in the neoclassical growth model as follows:

Capital deepening occurs when the stock of capital grows more rapidly than the labor force. In the absence of technological change, capital deepening will produce a growth of output per worker, of the marginal product of labor, and of real wages; it also will lead to diminishing returns on capital and therefore to a decline in the rate of return on capital.
We can analyze the effect of capital accumulation by using Figure 1. This figure shows the aggregate production function graphically by depicting output per worker on the vertical axis and capital per worker on the horizontal axis. In the background and held constant for the moment, are all the other variables that were discussed at the start of this section – the amount of land, the endowment of natural resources, and, most important of all the technology used by the economy (Samuelson and Nordhaus, 2005).

3.2. Geometrical Analysis of the Neoclassical Model

As the amount of capital per worker increases output per worker also increases. This graph shows the importance of "capital deepening" or increasing the amount of capital each worker has on land. Remember, however, that other factors are held constant, such as technology, quality of the labor force, and natural resources.

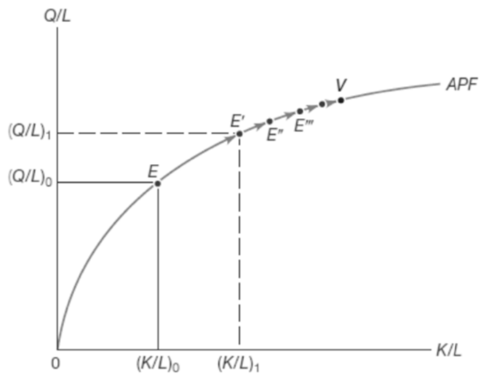


Figure 1. Aggregate production function. Source: Samuelson and Nordhaus, 2005

What happens as the society accumulates capital? As each worker has more and more capital with, the economy moves up and to the right on the aggregate production functions. Say that the capital ratio increases, from $(K/L)_0$ to $(K/L)_1$. Then the amount of output per worker increases, from $(Q/L)_0$ to $(Q/L)_1$.

What happens to the factor prices of labor and capital? As capital deepens, diminishing returns to capital set in, so the rate of return on capital and the real interest rate fall. (The slope of the curve in Figure 1 is the marginal product of capital, which is seen to fall as capital deepening occurs.) Also, because each worker can work with more capital, workers' marginal productivities rise, and the real wage rate consequently also rises. The reverse would happen if the amount of capital per worker were to fall for some reason. For example, wars tend to reduce much of a nation's capital to rubble and lower the capital-labor ratio.; after wars, therefore, we see a scarcity of capital and high returns on capital. Hence, our earlier verbal summary of the impact of capital deepening is verified by the analysis in Figure 1 (Samuelson and Nordhaus, 2005).

3.3. Long-Run Steady State

What is the long-run equilibrium in the neoclassical growth model without technological change? Eventually, the capital-labor ratio will stop rising. In the long run, the economy will enter a steady state in which capital deepening ceases, real wages stop growing, and capital returns and real interest rates are constant.

We can show how the economy moves toward the steady state in Figure 1. As capital continues to accumulate, the capital-labor ratio increases as shown by the arrows from E' to E'' to E''' until finally the capital-labor ratio stops growing at V. At that point, output per worker (Q/L) is constant, and real wages stop growing.

Without technological change, output per worker and the wage rate stagnate. But the long-run equilibrium of the neoclassical growth model makes it clear that of economic growth consists only of accumulating capital through replicating factories with existing methods of production, then the standard of living will eventually stop rising.
(Samuelson and Nordhaus, 2005)

4 System dynamics

According to Radzicki (2009), system dynamics is a computer simulation modeling methodology that is used to analyze complex nonlinear dynamic feedback systems for the purposes of generating insight and designing policies that will improve system performance.

System dynamics was created during the mid-1950s by Professor Jay Forrester of the Massachusetts Institute of Technology. Forrester's insights into the common foundations that underlie engineering, which led to the creation of system dynamics, were triggered, to a large degree, by his involvement with managers at General Electric during the mid-1950s. From hand simulations (or calculations) of the stock-flow-feedback structure of the GE plants, which included the existing corporate decision-making structure for hiring and layoffs, Forrester was able to show how the instability in GE employment was due to the internal structure of the firm and not to an external force such as the business cycle. These hand simulations were the start of the field of system dynamics (Radzicki, 1997).

As Bureš and Režný (2018) state, system dynamics is not a mainstream approach to modelling environment-economy systems. However, the application of the system dynamics approach can be very fruitful. From a methodological point of view, it can provide an alternative perspective on modelled systems to investigators.

System dynamics is an approach that helps develop a strategic view of a system, which could be an industry, society, or nation, by modeling the different parts and simulating the dynamics of interaction among the different parts. Modeling helps to determine changes over time and develop a view that cannot be obtained from spot studies conducted with a few of the critical elements of the system or within the confines of a specific time (e.g., second, hour, day, or year). One of the most powerful elements of this approach is the ability to link elements and model the interdependencies of the various elements across disciplines (e.g., climatic science and civil engineering) (Mallic et al., 2014).

From a system dynamics perspective a system’s structure consists of stocks, flows, feedback loops, and limiting factors. Stocks can be thought of as bathtubs that accumulate/de-cumulate a system’s flows over time. Flows can be thought of as pipe and faucet assemblies that fill or drain the stocks. Mathematically, the process of flows accumulating/de-cumulating in stocks is called integration. The integration process creates all dynamic behavior in the world be it in a physical system, a biological system, or a socioeconomic system. Examples of stocks and flows in economic systems include a stock of inventory and its inflow of production and its outflow of sales, a stock of the book value of a firm's capital and its inflow of investment spending and its outflow of depreciation, and a stock of employed labor and its inflow of hiring and its outflow of labor separations.

From a system dynamics point of view, positive and negative feedback loops fight for control of a system's behavior. The loops that are dominant at any given time determine a system's time path and, if the system is nonlinear, the dominance of the loops can change over time as the system's stocks fill and drain. From this perspective, the dynamic behavior of any economy – that is, the interactions between the trend and the cycle in an economy over time – can be explained as a fight for dominance be- tween the economy's most significant positive and negative feedback loops.

In system dynamics modeling, stocks are usually conceptualized as having limits. That is, stocks are usually seen as being unable to exceed or fall below certain maximum and minimum levels. Indeed, an economic model that can generate, say, either an infinite and/or a negative workforce would be seen as severely flawed by a system dynamicist. As such, when building a model system dynamicists search for factors that may limit the amount of material or information that the model's stocks can accumulate. Actual socioeconomic systems possess many limiting factors including physical limits (e. g., the number of widgets a machine can produce per unit of time), cognitive limits (e. g., the amount of information an economic agent can remember and act upon), and financial limits (e. g., the maximum balance allowed on a credit card). When limiting factors are included in a system dynamics model, the system's approach to these factors must be described. Generally speaking, this is accomplished with nonlinear relationships. Figure 1 presents a simple system dynamics model that contains examples of all the components of system structure described above (Radzicki, 2009).

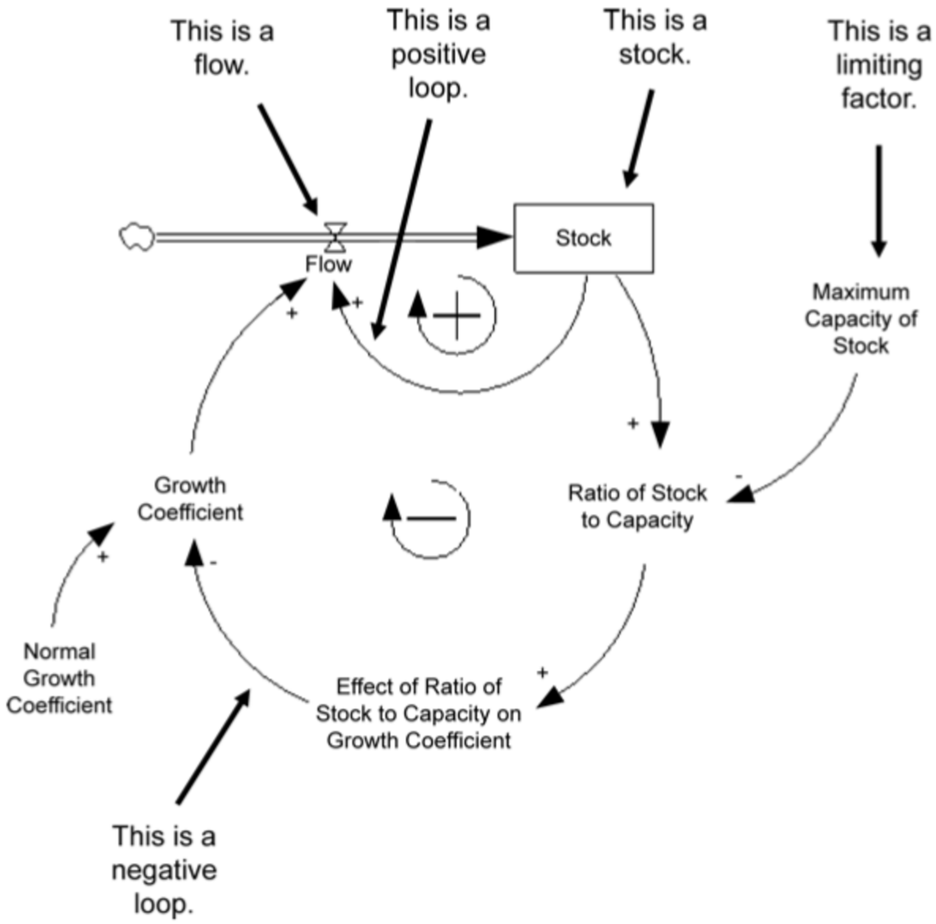


Figure 2. Simple system dynamics model containing examples of all components of system structure. Source: Radzicki, 2009

5 Integrated Assessment Models

5.1. Description

One of the most common approaches to evaluate the impact of climate change is to use an Integrated Assessment Model (IAM). These models integrate a model of the world economy with a representation of the global climate system. The models assess different scenarios from these complex systems and are used by governments when evaluating the impact of climate polices (e.g., estimating the Social Cost of Carbon) and informing the general public (Schwanitz, 2013).

Most economic studies of climate change, including most IAMs, integrate geophysical stocks and flows with economic stocks and flows. The major difference between IAMs and geophysical models is that economic measures include not only quantities but also valuations, which for market or near-market transactions are prices. The essence of an economic analysis is to convert or translate all economic activities into monetized values using a common unit of account, and then to compare different approaches by their impact on total values or a suite of values (Kumar, 2013).

IAMs can be divided into two general classes – policy optimization and policy evaluation models (Weyant et al. 1996). Policy evaluation models are generally recursive or equilibrium models that generate paths of important variables but do not optimize an economic outcome (Kumar, 2013).

There is also another classification of IAMs, that one distinguishes between firstly models that quantify developmental pathways or scenarios and provide detailed, sectoral information on the complex processes modelled. Here they are called process-based models. They have been used to explore different pathways for staying within climate policy targets such as the 1.5 °C target agreed upon in the Paris agreement. Notable modelling frameworks include IMAGE (Stehfest, 2014), MESSAGEix (Huppmann et al., 2019), REMIND-MAgPIE (Baumstark et al., 2021), and WITCH-GLOBIOM (Bosetti et al., 2006). Process-based models are the ones that IPCC relies on.

Secondly, there are models that aggregate the costs of climate change and climate change mitigation to find estimates of the total costs of climate change. These are called aggregate cost-benefit models. Cost-benefit integrated assessment models are the main tools for calculating the social cost of carbon, an estimate of the economic value of the extra (or marginal) impact caused by the emission of one more tone of carbon (in the form of carbon dioxide) at any point in time (IPCC Working Group II, 2007). This type of modelling is carried out to find the total cost of climate impacts, which are generally considered a negative externality not captured by conventional markets. To correct such a market failure, for instance by using a carbon tax, the cost of emissions is required. The examples of the aggregate cost-benefit models are FUND (Tol and Anthoff, 2014) and DICE (Nordhaus and Sztorc, 2013).

5.2. DICE

5.2.1. Model Description

The Dynamic Integrated Climate-Economy model, referred to as the DICE model or Dice model, is a neoclassical integrated assessment model developed by 2018 Nobel Laureate William Nordhaus. The DICE model views the economics of climate change from the perspective of neoclassical economic growth theory. In this approach, as it has been already mentioned, economies make investments in capital, education, and technologies, thereby reducing consumption today, in order to increase consumption in the future. The DICE model extends this approach by including the "natural capital" of the climate system. In other words, it views concentrations of greenhouse gases as negative natural capital, and emissions reductions as investments that raise the quantity of natural capital (or reduce the negative capital). By devoting output to emissions reductions, economies reduce consumption today but prevent economically harmful climate change and thereby increase consumption possibilities in the future (Nordhaus and Sztorc, 2013).

The DICE integrated assessment model has been developed in a series of reports, peer reviewed articles, and books by William Nordhaus and colleagues over the course of more than thirty years. The earliest precursor to DICE was a linear programming model of energy supply and demand with additional constraints imposed to represent limits on the peak concentration of carbon dioxide in the atmosphere. The model was dynamic, in that it represented the time paths of the supply of energy from various fuels and the demand for energy in different sectors of the economy and the associated emissions and atmospheric concentrations of carbon dioxide. However, it included no representation of the economic impacts or damages from temperature or other climate changes. Later, Nordhaus developed a long-run steady-state model of the global economy that included estimates of both the costs of abating carbon dioxide emissions and the long-term future climate impacts from climate change. This allowed for a balancing of the benefits and costs of carbon dioxide emissions to help determine the optimal level of near-term controls.

The model was first presented by William Nordhaus in a discussion paper for the Cowles Foundation in 1992, where he described the new, fully dynamic optimal growth structure of the model and the optimal time path of emission reductions and associated carbon taxes that emerged from it. The next major advance involved disaggregating the model into ten different groups of nations to produce the RICE (Regional DICE) model, which allowed the authors to examine national-level climate policies and different strategies for international cooperation. An update and extended description of both RICE (now with eight regions) and DICE appeared in the book by Nordhaus and Boyer (2000). The next major update of DICE, modified to include a backstop technology that can replace all fossil fuels and whose price was projected to decline slowly over time, appeared in another book by Nordhaus (2008). Finally, Nordhaus (2010) described the most recent version of the RICE model, which adds an explicit representation of damages due to sea level rise. The next major update of DICE, modified to include a backstop technology that can replace all fossil fuels and whose price was projected to decline slowly over time, appeared. (Newbold, 2010)

DICE is a modified optimal economic growth model, where an additional form of “unnatural capital”—the atmospheric concentration of CO_2—has a negative effect on economic output through its influence on the global average surface temperature. Global economic output is represented by a Cobb-Douglas production function using physical capital and labor as inputs. Labor is assumed to be proportional to the total global population, which grows exogenously over time. Total factor productivity also increases exogenously over time. The carbon dioxide intensity of economic production and the cost of reducing carbon dioxide emissions decrease exogenously over time. In each period a fraction of output is lost according to a climate change damage function. The output in each period is then divided between consumption, investment in the physical capital stock (savings), and expenditures on emissions reductions (akin to investment in the natural capital stock). DICE solves for the optimal path of savings and emissions reductions over a multi-century planning horizon, where the objective to be maximized is the discounted sum of all future utilities from consumption. Total utility in each period is the product of the number of individuals alive and the utility of a representative individual with average income in that period (Newbold, 2010).

5.2.2. Reception

The DICE and RICE models have received considerable attention from others studying the economic impact of climate change. It is one of the models used by the Environmental Protection Agency for estimating the social cost of carbon. For his work on climate change, William Nordhaus was awarded the *Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel.*

However, the model was widely criticised. A report from the Heritage Foundation, a conservative think tank, describes DICE model as “a useful academic exercise in anticipation of solving these very serious problems, the results at this time are nowhere near reliable enough to justify trillions of dollars of government policies and burdensome regulations” on account of its extreme sensitivity to the examined assumptions (Dayaratha, 2013).

Another piece of criticism of DICE model was introduced by Steve Keen (2020) of the Institute for Strategy, Resilience and Security of the University College London. In the report the model is criticised for a priori assuming that 87% of the economy will be unaffected by climate change, using fictional empirics, misrepresenting contributions from natural scientists, and selecting a high discount rate (Keen, 2020).

5.3. Stella

5.3.1. Tool Description

STELLA (short for Systems Thinking, Experimental Learning Laboratory with Animation) is a visual programming language for system dynamics modeling introduced by Barry Richmond in 1985. The program, distributed by isee systems allows users to run models created as graphical representations of a system using four fundamental building blocks. STELLA has been used in academia as a teaching tool and has been utilized in a variety of research and business applications. The program has received positive reviews, being praised in particular for its ease of use and low cost. (Wikipedia, 2016)

STELLA's approach to modeling systems shares some similarities with a precursor, the DYNAMO simulation language. DYNAMO explicitly defined "stocks" and "flows" as key variables in a system, a vocabulary which STELLA shares. Within STELLA, users are presented with a graphical user interface in which they may create graphical models of a system using four fundamentals: stocks, flows, converters, and connectors. Relationships between converters (which convey transforming variables) and other elements may be drawn with converters. Users are able to input values for stocks, flows, and converters (including with a variety of built-in functions). STELLA does not differentiate between external and intermediate variables within a system; all of them are represented with converters.

The software produces finite difference equations that describe the graphical model and allows users to select a numerical analysis method to apply to the system. Before running a model, users may also specify a time step and runtime for the simulation. STELLA can output data in graphical or tabular forms. (Wikipedia, 2016)

5.3.2. The Stella Toolbars & Model building in Stella

The Stella toolbars allows user to accomplish the ordinary tasks that one performs as a part of model building.

The Build Toolbar contains the components one needs to build models. By default, it sits in the upper left-hand portion of the window.

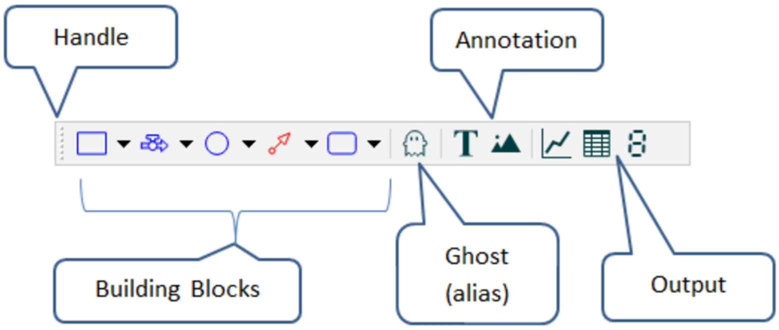


Figure 3. Build Toolbar in Stella. Source: isee systems, 2018

The Mode toolbar can be used to switch between the Map () and Model (x^2) views, for looking at structure. It also allows you to change between Edit mode (where you can make changes to your model) and Explore mode (where you can investigate model structure and behavior without changing anything), as well as to open the Results Panel or Causal Lens™ (both of which will also switch you to Explore mode). In Stella Architect, there's a button to open the Interface Window. If you're inside of a module, there will be buttons to move to the parent module and the home (Top-Level) module. Finally, there's a zoom control that can be used to set zoom level when looking at model structure (isee systems, 2018).

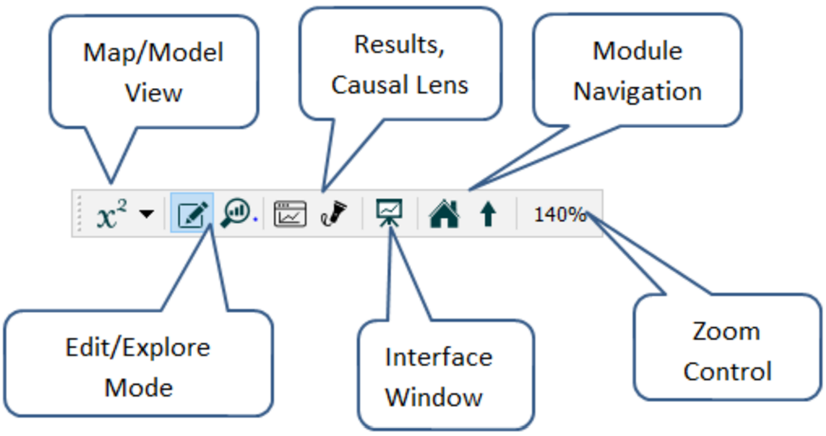


Figure 4. Model Toolbar in Stella. Source: isee systems, 2018

The Run toolbar lets you start, pause, and stop runs. You can also slide through the current run, to view results at different times (isee systems, 2018).

Figure 5. Run Toolbar in Stella. Source: isee systems, 2018

6 Simple DICE Model

The economic growth component of the model is a variation of the Solow-Swan growth model. Output Q_t is produced by the combination of capital K_t, labor L_t, and technology A_t according to the Cobb-Douglas production function.

$$Q_t = A_t * K_t^{\alpha} * L_t^{(1-\alpha)} \tag{2}$$

6.1. Population

Labor is represented by the population L_t in the model. The initial value of population is 7.5 billion people, population growth is 180.75 million people every 5 years so that the population gradually grows to UN prediction of 11 billion people by 2095.

$$L(t) = L(t-1) * Lg \tag{3}$$

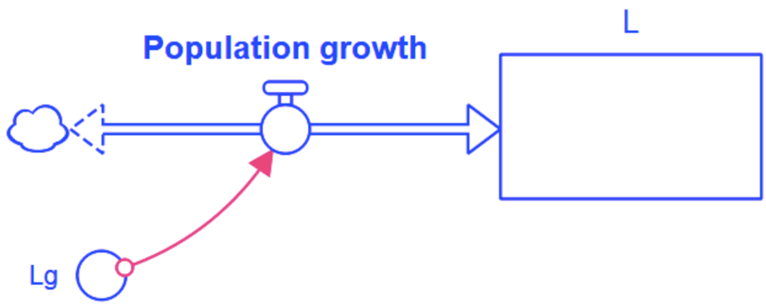


Figure 6. Model's population structure. Source: own work.

Parameter	Value	Unit
Population L	7.5	Billion people
Population growth rate L_g	0.1875	Dimensionless

Table 1. Parameters of population structure of the model. Source: own work.

6.2. Capital

K_t is gross capital in time t, δ then stands for the capital depreciation, and I is investments.

$$K(t) = K(t-1) * (1 - \delta) + I(t-1) \quad (4)$$

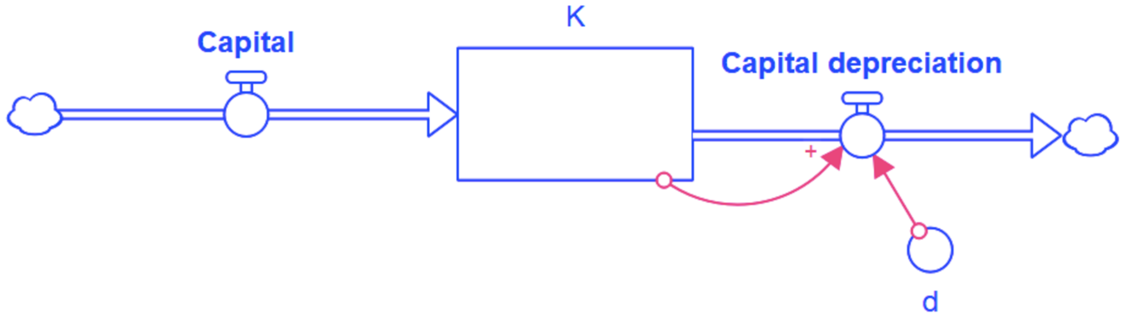


Figure 7. Capital sector structure. Source: Marek, 2020.

Parameter	Value	Unit
Initial value of capital K	223	Trillion USD
d	0,1	Dimensionless

Table 2. Parameters of capital sector of the model. Source: Nordhaus, 2020.

6.3. Technological efficiency

A_t represents technological efficiency or total factor productivity (TFP) in time t.

$$A(t) = A(t-1) * Ag \quad (5)$$

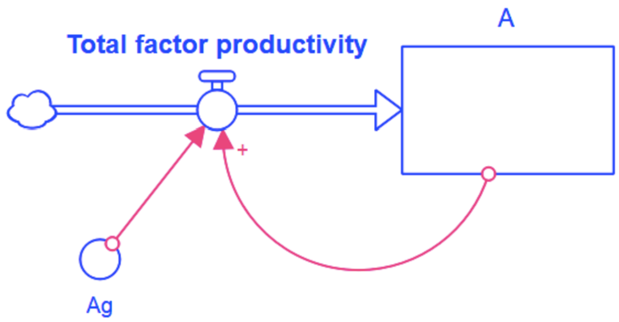


Figure 8. Technological efficiency sector of the model. Source: Marek, 2020.

Parameter	Value	Unit
A	5.115	Dimensionless
Growth rate A_g	1.067	Dimensionless

Table 3. TFP in the model. Source: Nordhaus, 2020.

6.4. Emission intensity

Economic activity, such as heating, transportation, and manufacturing, requires energy. The major source of energy in modern economies is from fossil fuels, coal, petroleum, and natural gas. This means that economic activity produces emissions, called 'Industrial emissions' in DICE. The richer we are, the greater the emissions, and conversely, the poorer we are, the lower the emissions. Over time, the economy has got more efficient: it is possible to produce the same amount using less energy. DICE includes this effect by estimating the 'energy intensity' of the economy: how much output we can produce with a given amount of energy. So 'emission intensity' is in fact emission-to-output ratio and is measured in megatonnes of CO_2 per 1000 2010 US dollars.

$$\sigma(t) = \sigma(t-1) * \sigma_g \tag{6}$$

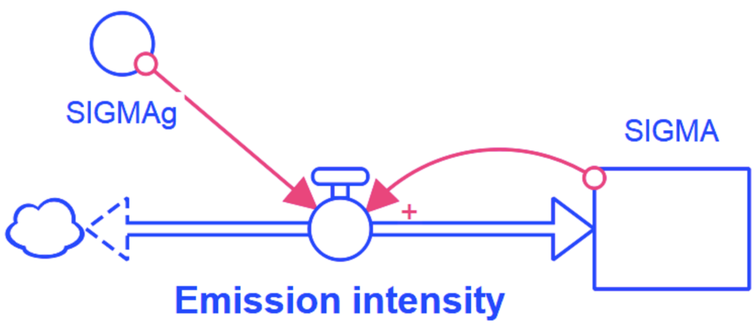


Figure 9. Emission intensity in the model. Source: own work.

Parameter	Value	Unit
Emission intensity σ	0.350	$MtCO_2$ / 1000 2010 US$
Emission intensity growth rate σ_g	0.9277	Dimensionless

Table 4. Parameters of emission intensity in the model. Source: Nordhaus, 2020.

6.5. Carbon emission from land usage

Forests absorb CO_2 as trees and other plants grow. If we cut down or burn down forests, we reduce the amount of CO_2 that they absorb, leaving more CO_2 in the atmosphere. We can treat the additional CO_2 as the equivalent of emissions. DICE includes these emissions, but they contribute only a limited amount overall.

$$E0(t) = E0(t-1) * E0_g \quad (7)$$

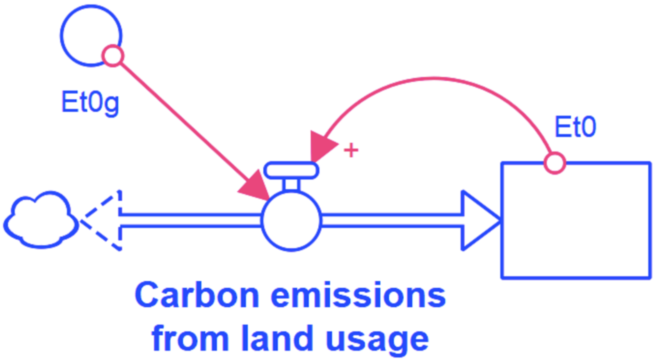


Figure 10. Carbon emissions from land usage sector of the model. Source: own work.

Parameter	Value	Unit
Non-industrial emission Et_0	2.6	$GtCO_2$
Growth rate of non-industrial emission Et_{0g}	0.885	Dimensionless

Table 5. Parameters of non-industrial emission of the model. Source: Nordhaus, 2020.

6.6. Emissions control

The emissions control rate is the fraction of emissions that are reduced or controlled by a climate change policy. For example, if a climate change policy limits emissions to 80% of what they otherwise would have been, the control rate is 20%.

$$\mu(t) = \mu(t-1) * \mu_g \quad (8)$$

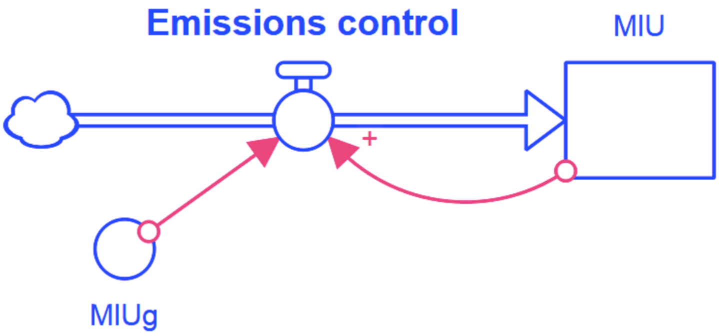


Figure 11. Emissions control sector of the model. Source: own work.

Parameter	Value	Unit
Emission control μ	0.029	Dimensionless
Emission control growth rate μ_g	1.080	Dimensionless

Table 6. Parameters of emissions control in the model. Source: Nordhaus, 2020.

6.7. Total CO_2 emissions

CO_2 emissions Et consist of industrial and non-industrial (land-use) emissions. Total CO_2 emissions are then given by

$$E(t) = \sigma(t) * (1 - \mu(t)) * Q(t) + E0(t) \tag{9}$$

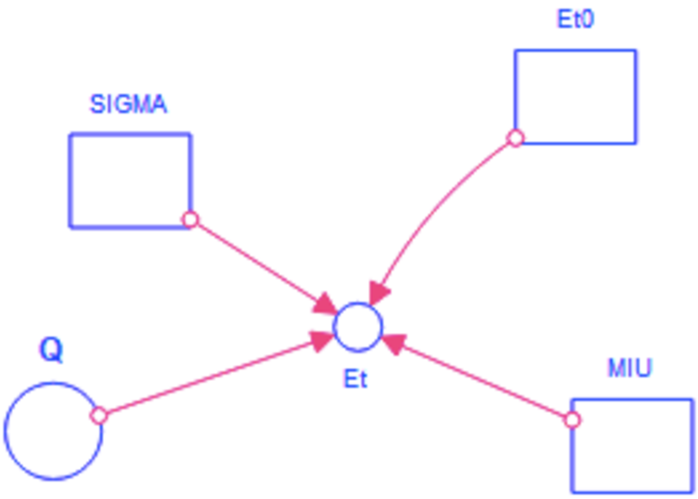


Figure 12. Total CO_2 emission in the model. Source: own work.

6.8. CO_2 concentration

The carbon mass in the atmosphere is the total amount, by mass, of carbon in the atmosphere in a given period. It includes both naturally occurring carbon and carbon emitted through the use of fossil fuels.

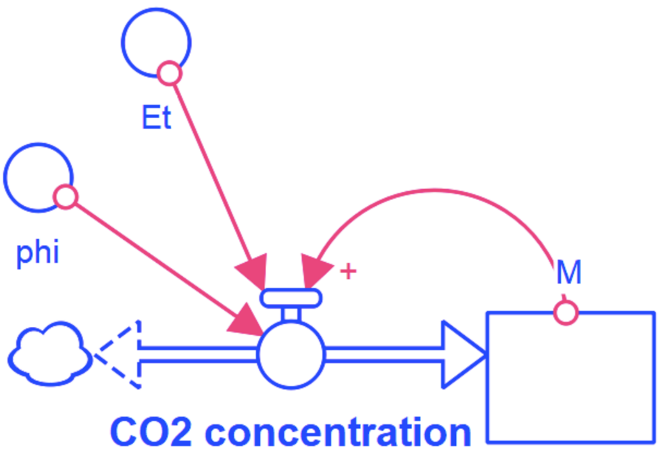


Figure 13. CO2 concentration in the model. Source: own work.

Parameter	Value	Unit
CO_2 concentration M	851	$GtCO_2$
ϕ	1.013	Dimensionless

Table 7. Parameters of CO_2 concentration in the model. Source: Nordhaus, 2020.

6.9. Temperature increase

Temperature increase H (degrees Celsius from 1900).

$$H(t) = \eta_0 + \eta_1 * H(t-1) + \eta_2 \ln M(t) \quad (10)$$

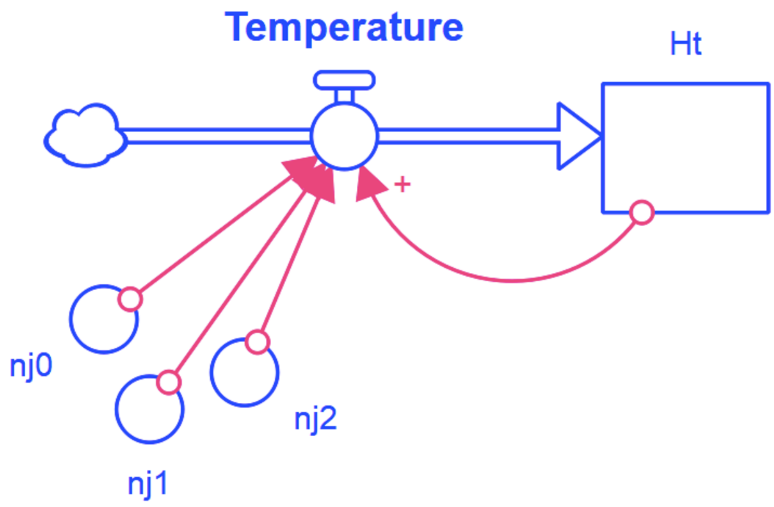


Figure 14. Temperature increase in the model. Source: own work.

Parameter	Value	Unit
H	0.85	°C from 1900
η_0	-2.8672	Dimensionless
η_1	0.8954	Dimensionless
η_2	0.4622	Dimensionless

Table 8. Parameters of temperature increase in the model. Source: Ikefuji et al., 2021.

6.10. Abatement cost coefficient

Auxiliary variable for the abatement cost. The initial value and the growth rate are taken from the original DICE model.

$$\psi(t) = \psi(t-1) * \psi_g \tag{11}$$

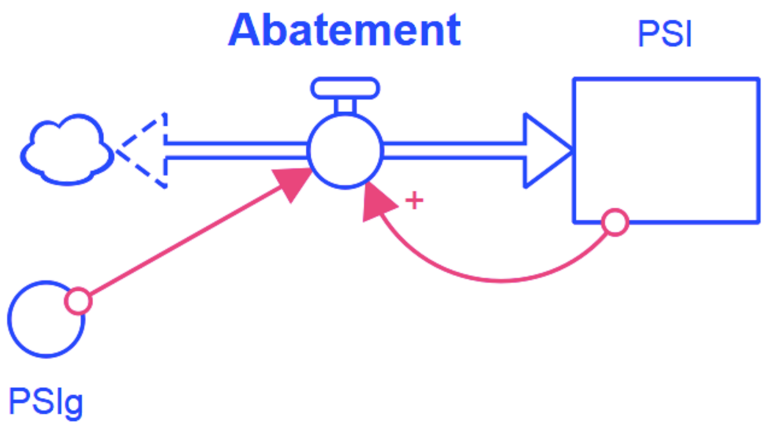


Figure 15. Abatement in the model. Source: own work.

Parameter	Value	Unit
Abatement coefficient ψ	0.0067	Dimensionless
Abatement coefficient growth rate ψ_g	0.9065	Dimensionless

Table 9. Parameters of abatement in the model. Source: Nordhaus, 2020.

6.11. Abatement

Reducing emissions costs money. These costs are called abatement costs. The model specifies abatement costs as a fraction of the total output: this is the portion of GDP that we spend replacing fossil fuel energy with clean energy.

$$\omega(t) = \psi(t) * \mu(t)^2 \tag{12}$$

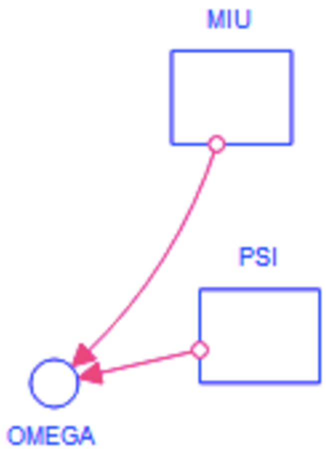


Figure 16. Abatement in the model. Source: own work

6.12. Damage

The damage-abatement function is DICE specifies two fractions, ω(t) (abatement) and ξ * H^2(t) (damage), of Q(t) which reduce Q(t) so that less money is available for investment and consumption along the budget constraint.

In the model, this fraction is specified as

$$\frac{1-\omega}{1+\xi * H^2} \tag{13}$$

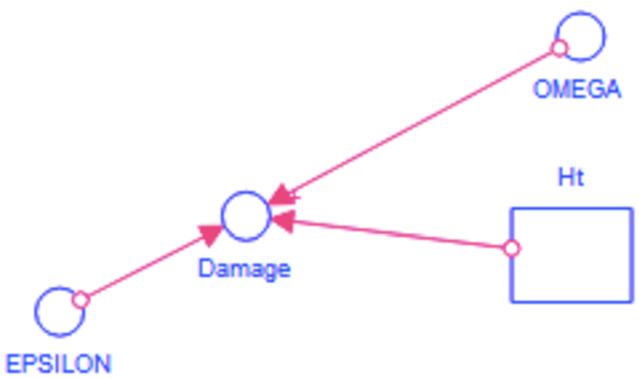


Figure 17. Damage in the model. Source: own work

Parameter	Value	Unit
Damage coefficient ξ	0.00265	Dimensionless

Table 10. Parameters of abatement in the model. Source: Ikefuji et al., 2021

6.13. Gross product

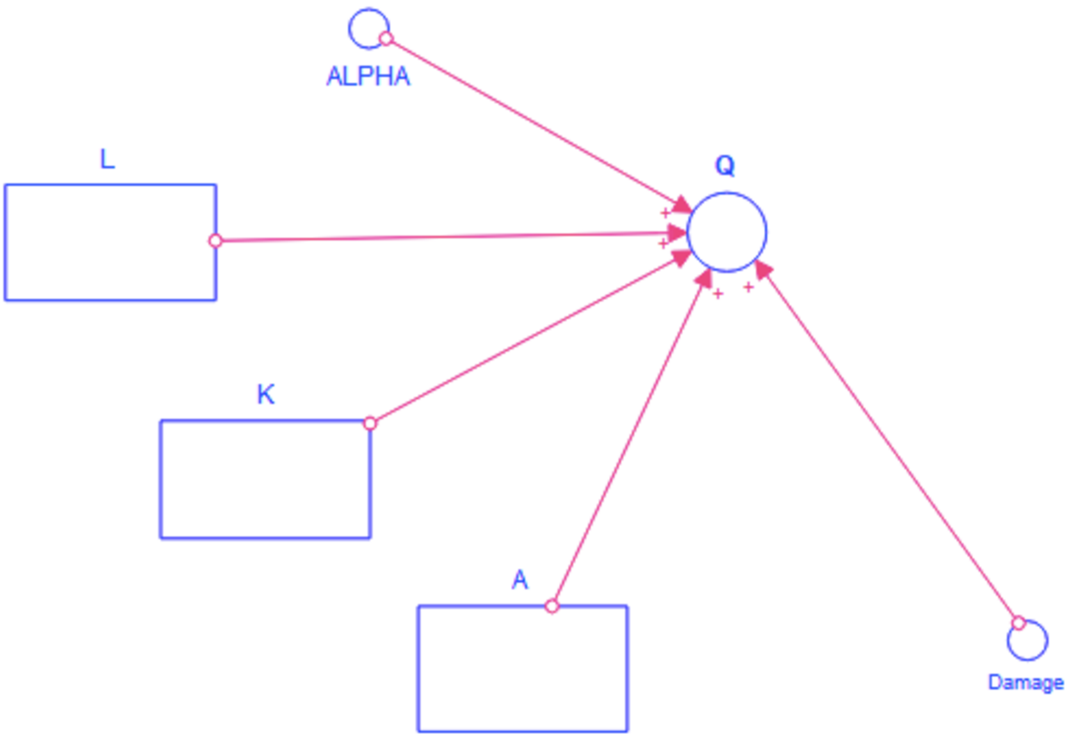


Figure 18. Gross product in the model. Source: own work

$$Q(t) = A * K^{\alpha} * L^{1-\alpha} * Damage \quad (14)$$

Parameter	Value	Unit
Total factor productivity *(A)*	5.115	Dimensionless
Capital (*K*)	223	Trillion USD
Labor (*L*)	7.5	Billion people
Elasticity of output (*ALPHA*)	0.3	Dimensionless

Table 11. Parameters of gross product in the model. Source: own work.

7 Simulation & Outcomes

In this part the simulation will be conducted. There will be models of two economies – C (for climate) and NC (non-climate).

7.1. Initial state

Timeline of the model is 2015-2095 (labeled 1-17 in the model). Timestep is 5 years, as in the original DICE model.

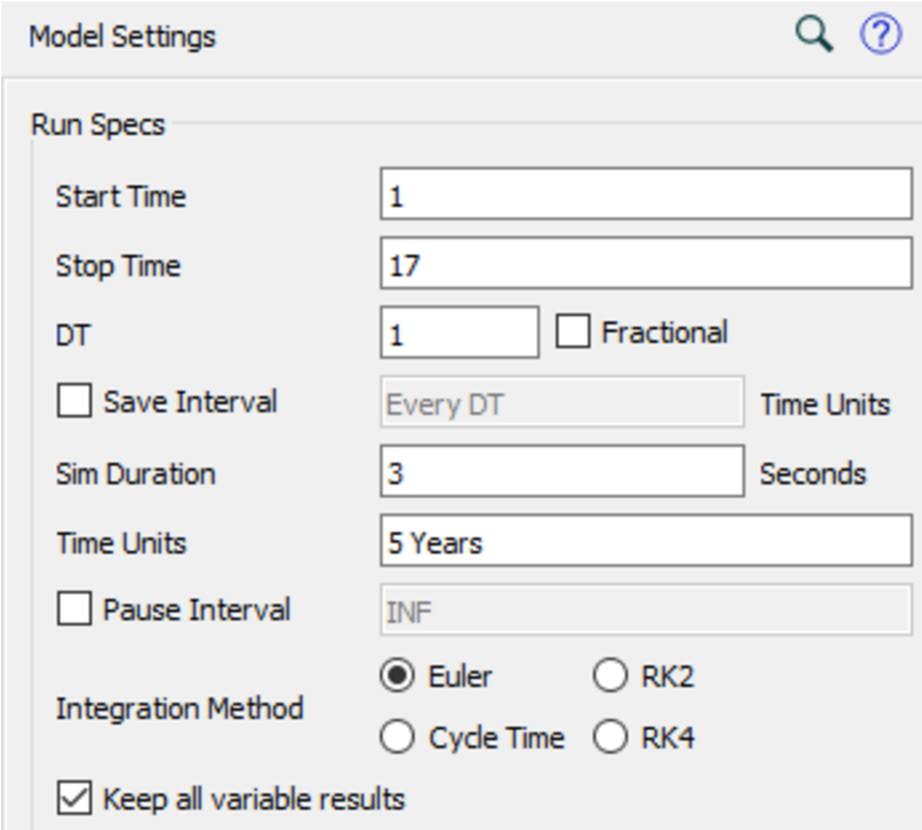


Figure 19. Model settings in Stella. Source: own work.

7.2. Economy C

Variables and their parametrization in the model of economy C. Preview of the model is in Appendix A.

Parameter (*Name in the model*)	Value
Population L (*L*)	7.5
Population growth rate L_g (*Lg*)	0.21566
Capital K (*K*)	223
Capital depreciation rate d (*d*)	0,1
Total factor productivity (TFP) A (*A*)	5.115
TFP growth rate A_g (*Ag*)	1.067
Elasticity of output α (*ALPHA*)	0.3
Saving rate S_g (Sg)	0.22
Emission intensity σ (*SIGMA*)	0.350
Emission intensity growth rate σ_g (*SIGMAg*)	0.9277
Non-industrial emission Et_0 (*Et0*)	2.6
Growth rate of non-industrial emission Et_{0g} (*Et0g*)	0.885
Emission control μ (*MIU*)	0.029
Emission control growth rate μ_g (*MIUg*)	1.080
CO_2 concentration M (*M*)	851
Auxiliary CO_2 concentration variable ϕ (*phi*)	1.013
Temperature change H (*H*)	0.85
Temperature auxiliary variable η_0 (*nj0*)	-2.8672
Temperature auxiliary variable η_1 (*nj1*)	0.8954
Temperature auxiliary variable η_2 (*nj2*)	0.4622
Abatement coefficient ψ (PSI)	0.0067
Abatement coefficient growth rate ψ_g (PSIg)	0.9065
Damage coefficient ξ	0.00265

Table 12. Parameters of the model C. Source: own work.

7.3. Economy NC

Variables and their parametrization in the model of economy NC. Preview of the model is in Appendix B.

Parameter (*Name in the model*)	Value
Population L (*L*)	7.5
Population growth rate L_g (*Lg*)	0.21566
Capital K (*K*)	223
Capital depreciation rate d (*d*)	0,1
Total factor productivity (TFP) A (*A*)	5.115
TFP growth rate A_g (*Ag*)	1.067
(*ALPHA*)	0.3
(Sg)	0.22

Table 13. Parameters of the model NC. Source: own work.

7.4. APL

Auxiliary info converter is added to both models called APL (APL[NC] in the economy NC), which stands for average product of labor:

$$APL = Q/L \tag{15}$$

7.5. Outcomes & Findings

The following graphs show the results of the model run for years 2015 – 2095. On the left side graphs show the whole period of the run, 2015 – 2095, on the right side there are graphs of the same run and variables, but for the years 2065 – 2095 for better overview of the growing difference between two economies.

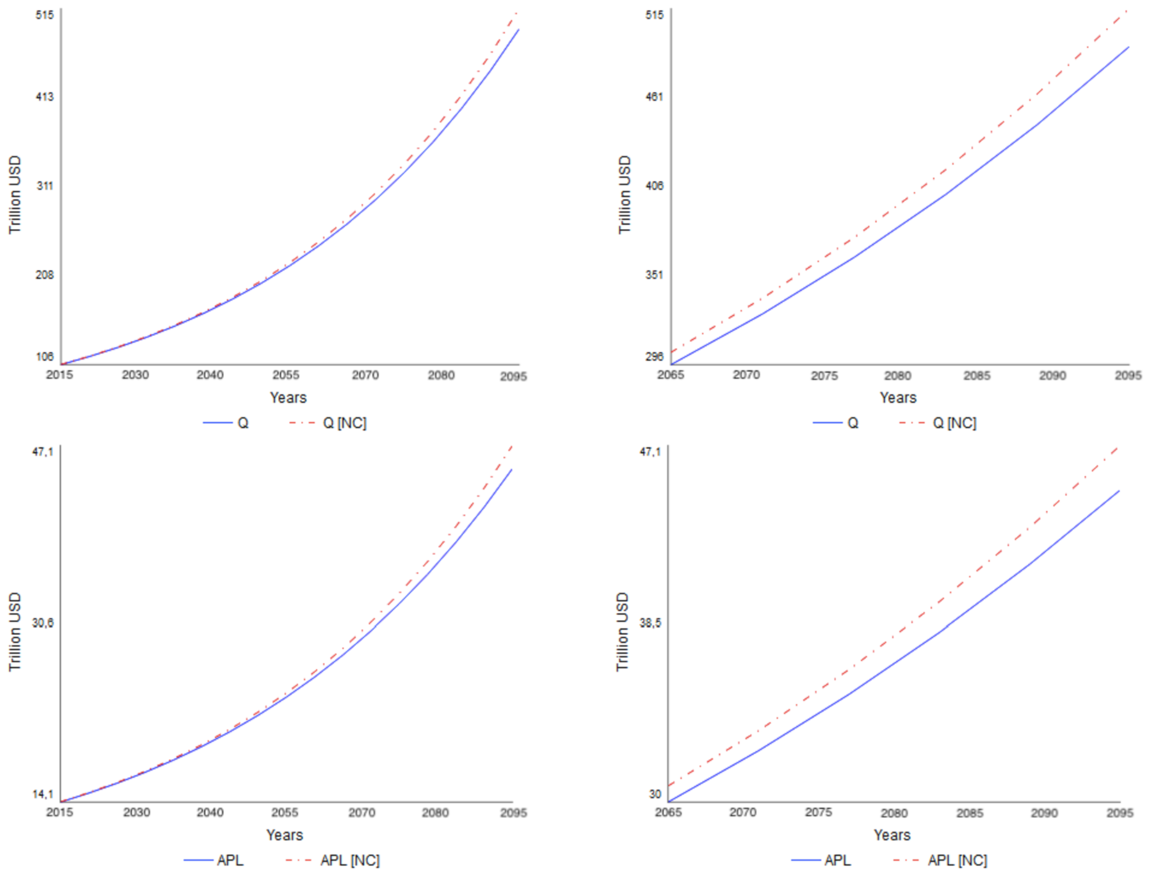


Figure 20. Graphs of the chosen parameters of the model. Source: own work.

Year	Q, Trillion USD	Q [NC], Trillion USD	Absolute change, Trillion USD	Relative change, %
2075	296	304	8	2.70
2080	327	337	10	3.06
2085	362	374	12	3.32
2090	401	416	15	3.74
2095	444	463	19	4.28
2095	492	515	23	4.67

Table 14. Values and comparison of parameters Q and Q[NC]. Source: own work.

Year	APL, Trillion USD	APL [NC], Trillion USD	Absolute change, Trillion USD	Relative change, %
2075	30	30.8	0.8	2.67
2080	32.4	33.4	1.0	3.09
2085	35.1	36.3	1.2	3.42
2090	38.1	39.6	1.5	4.27
2095	41.4	43.1	1.7	4.11
2095	44.9	47.1	2.2	4.90

Table 15. Values and comparison of parameters APL and APL[NC]. Source: own work.

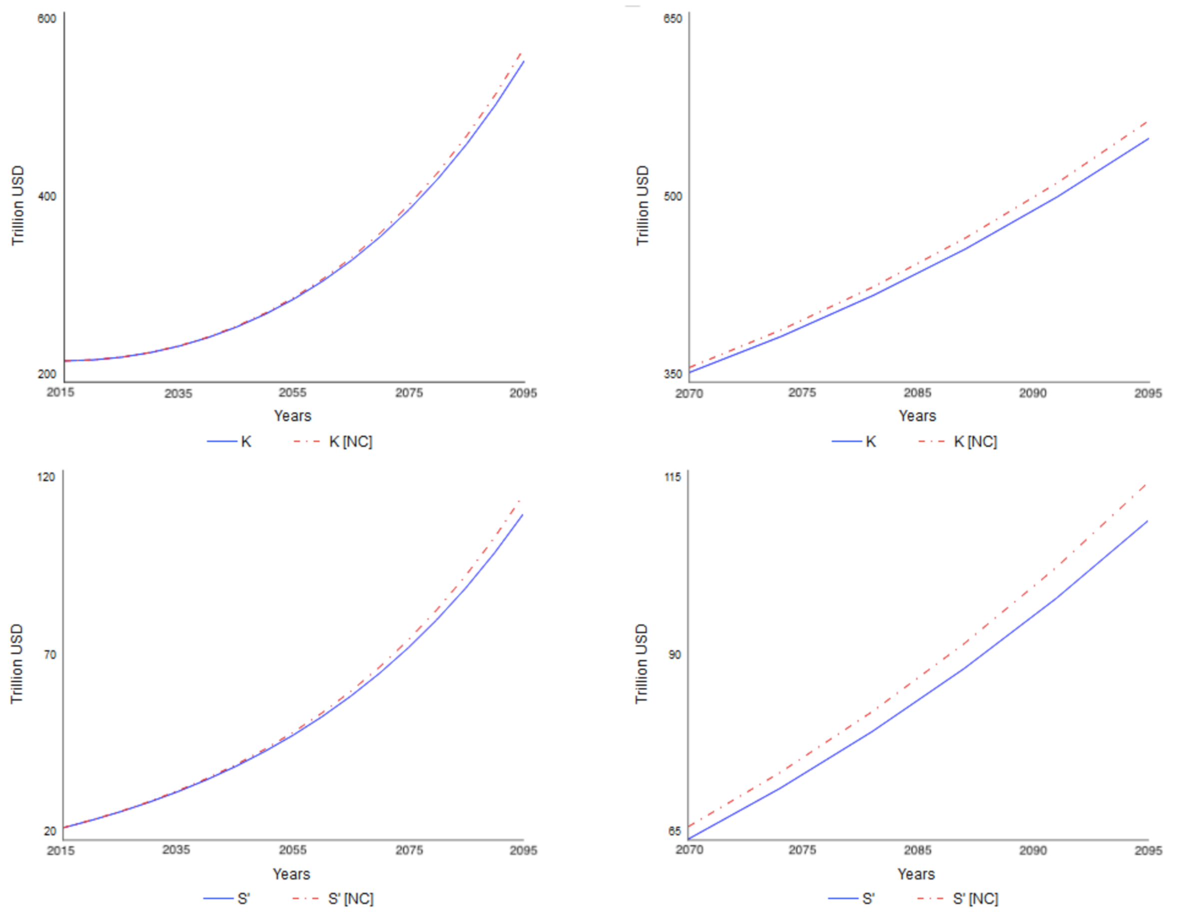


Figure 21. Graphs of the chosen economic parameters of the model. Source: own work.

Year	K, Trillion USD	K[NC], Trillion USD	Absolute change, Trillion USD	Relative change, %
2075	358	362	4	1.12
2080	387	392	5	1.29
2085	420	427	7	1.66

2090	458	467	9	1.97
2095	500	512	12	2.40
2095	548	563	15	2.74

Table 16. Values and comparison of parameters K and K[NC]. Source: own work.

Year	S, Trillion USD	S[NC], Trillion USD	Absolute change, Trillion USD	Relative change, %
2075	65.1	66.8	1.7	2.61
2080	72	74.1	2.1	2.92
2085	79.7	82.4	2.7	3.39
2090	88.2	91.6	3.4	3.86
2095	97.7	102	4.3	4.40
2095	108	113	5.0	4.63

Table 17. Values and comparison of parameters S and S[NC]. Source: own work.

One could see from the given graphs that total outcome in economy NC is higher by the year 2095 by 23 trillion dollars or 4.67% with the gap between two economies constantly growing. This than has effect on other economic indicators, such as APL, capital, and savings, where the effect is similar – in years 2015 – 2095 economy with the influence of climate, its change and abatement, has lower outcomes than pure Solow-Swan neoclassical economy. In the created model total output grows exponentially, which corresponds to the original DICE model.

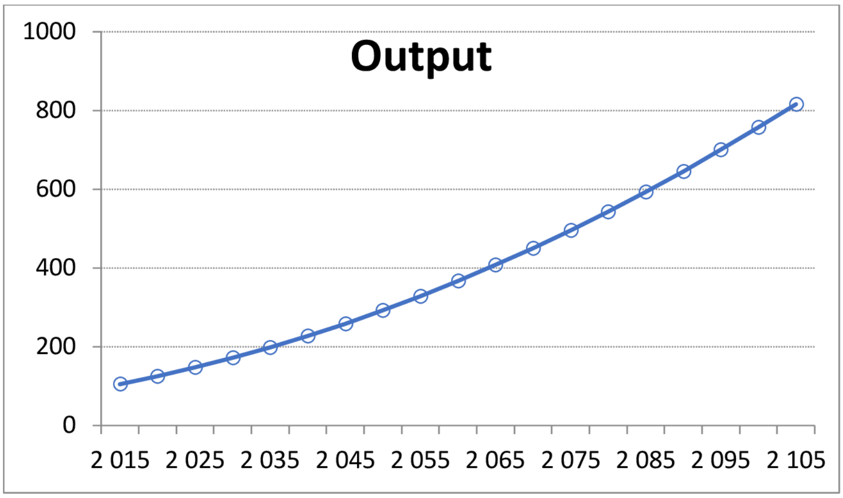


Figure 22. Output graph in the original DICE. Source: Nordhaus, 2020.

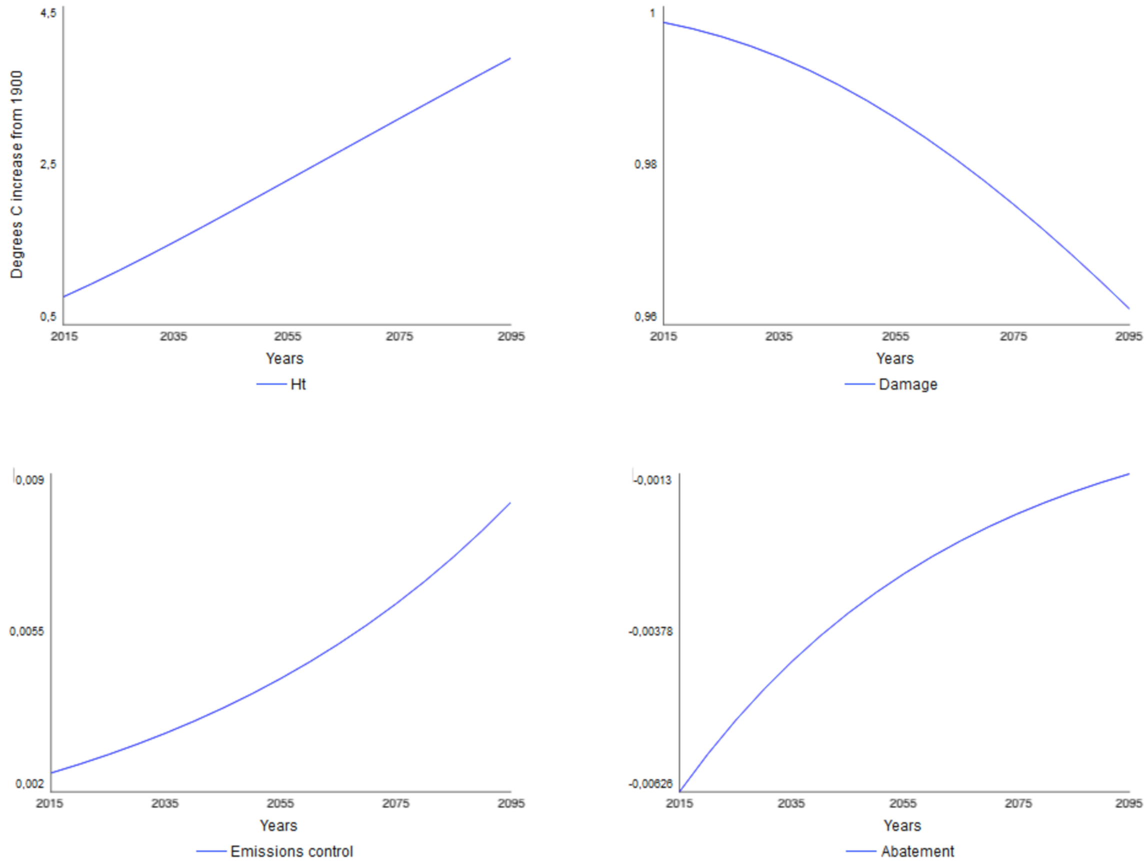


Figure 23. Graphs of the chosen climate-related parameters of the model. Source: own work.

For economy C, some climate-related indicators are presented in addition. Damage, emission control, and abatement were calibrated by averaging respective parameters of DICE-2016R model for years 2015 – 2095 and correspond to the values in DICE-2016R when being added to the model. One could see that according to outcomes, emission control and abatement are growing in years 2015 – 2095. Although damage function is declining, the damage is in fact growing, as the function is inverse and represents the fraction of the gross output that should be left after the damages.

The temperature change in the Simple DICE model corresponds to the temperature change in the original DICE model, with the temperature increase of 3.85 in comparison to year 1900.

7.6. Sensitivity Analysis

To test the robustness of the results, we will conduct a sensitivity analysis. The scope of the analysis is going to be on the damage coefficient ξ (named *EPSILON* in the model). Stella Professional has its own tool for sensitivity analysis, which can be found in section "Model Analysis Tool" in Run Specs.

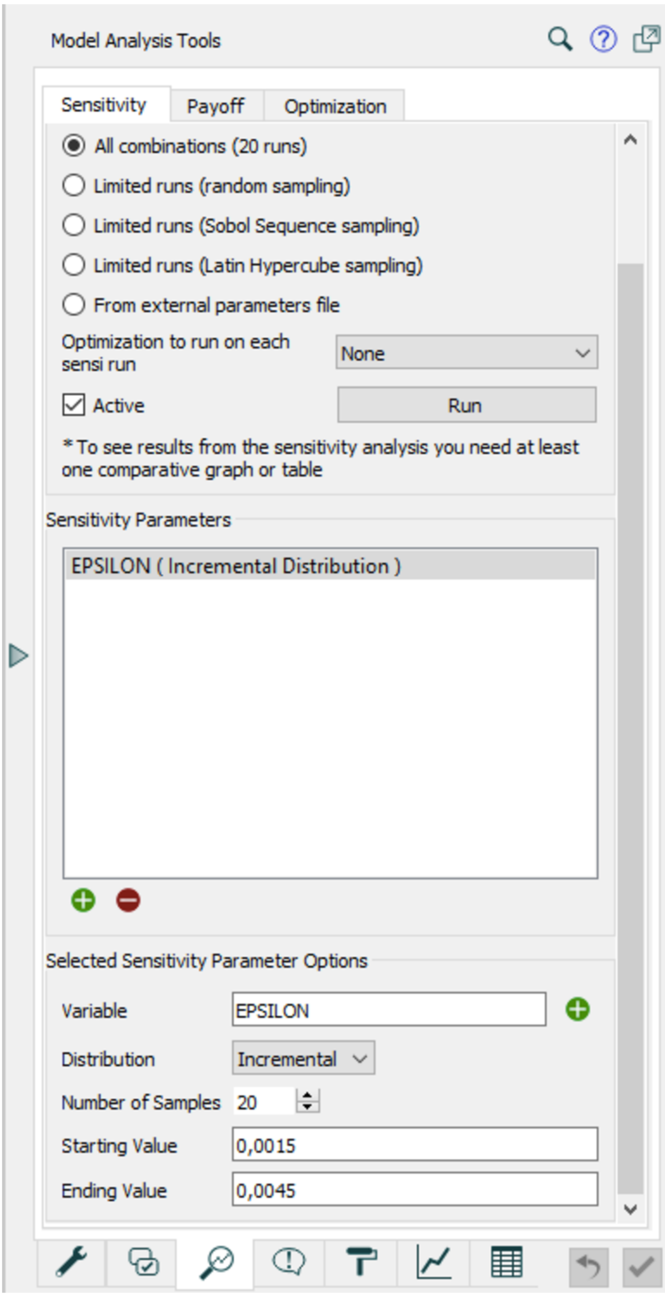
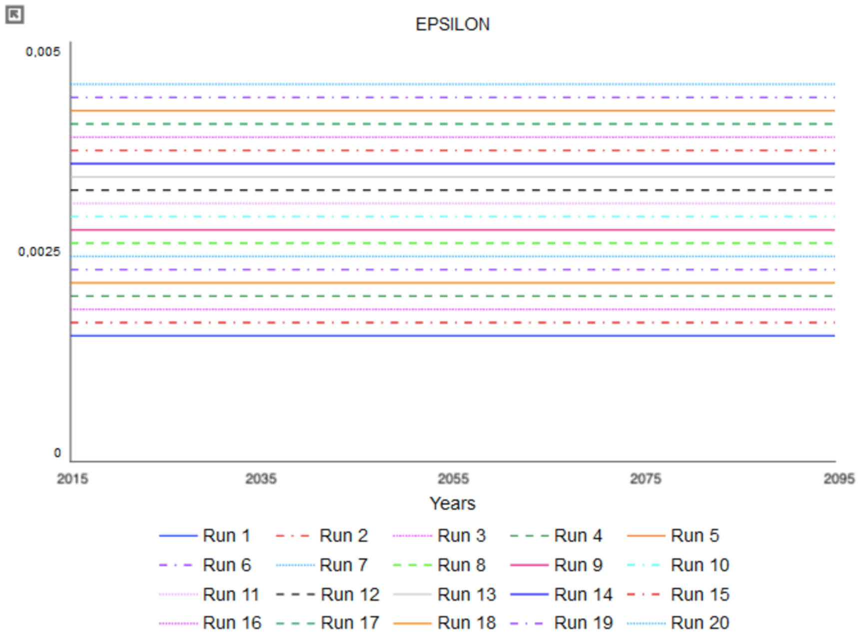


Figure 24. Settings of the sensitivity analysis in Stella. Source: own work.



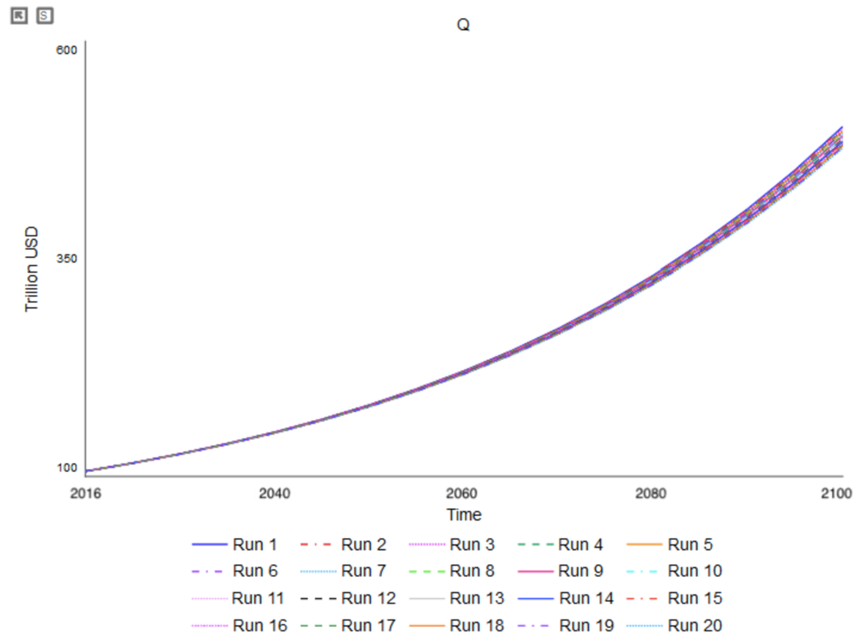


Figure 25. Sensitivity analysis graphs. Source: own work.

In 20 runs different values from 0.0015 to 0.0045 of damage coefficient ξ were tested by the software. The values of total output Q in the 20 runs varies from 477 to 502 trillion USD. But one could see that tested changes of damage coefficient ξ didn't change the nature of output growth, which stays exponential notwithstanding the changes of the values of ξ.

8 Discussion

Although the aim of the work was fulfilled, it is worth mentioning, that the model is only a simplified simulation of the DICE model, that does not have a precise calibration to the real data from the original model. The reality (of the DICE model) is different and contains a lot more variables and more complex equations that were not added to the simplified model. Created model is only a mere guide for undergraduate students in their first insights into the problem that shows how the economy could behave with the influence of climate and its change.

Just as an original DICE model, the built one has poor assumptions which lead to, for example, the model showing absurd result of constant world GDP growth even with a temperature change of 20°C in comparison to year 1900. Not only economic growth is clearly impossible under these circumstances, but ecologists agree, that already a 10°C growth would lead to sustained 'wet bulb' temperatures that would be fatal for humans in the Tropics and much of sub-tropics.

The built model also does not appreciate the role of energy in production. Energy is directly needed to produce GDP, and therefore if energy production must fall because of global warming, then so will GDP. The model also does not include 'unexpected' changes in energy situation, as the current one in Europe.

Therefore, the model could be useful as an educative tool in, for instance, MAEK II course, as the issue is discussed there. But UHK possesses only Stella Professional, that enables a user to do just system modelling and simulation. For educational purposes Stella Architect is much more suitable, as it offers not only modelling and simulation functionality, but also interface creation. With growing interest for system modelling among the students at the university, implementation of Stella Architect would be much appreciated and bring positive effects to the development of system dynamics at the university.

9 Conclusion

The goal of the paper was to create and simulate a model of economy with the climate module and show the differences in gross output in comparison to the textbook neoclassical model of economic growth.

In the review of related literature of the thesis the theoretical basis was presented, according to which the model then was implemented, that interpreted described theory to system dynamics. The Solow-Swan neoclassical model of economic growth and Nordhaus' DICE model were described. Afterwards a simulation of two was conducted - in which the difference in outputs between two models was shown.

The work itself then led the reader through the building of the Simple DICE model, showing and describing each step of the model creation in STELLA Professional modelling tool. When the model is built, it was then tested for the period of 2015 – 2095. Results were compared to the pure non-climate economy. Total outcome by the year 2095 in non-climate economy NC was 515 trillion 2015 US dollars, which was higher by 23 trillion dollars or 4.67% than the total outcome of Simple DICE model economy, which was only 492 trillion 2015 US dollars, with the gap between two economies constantly growing.

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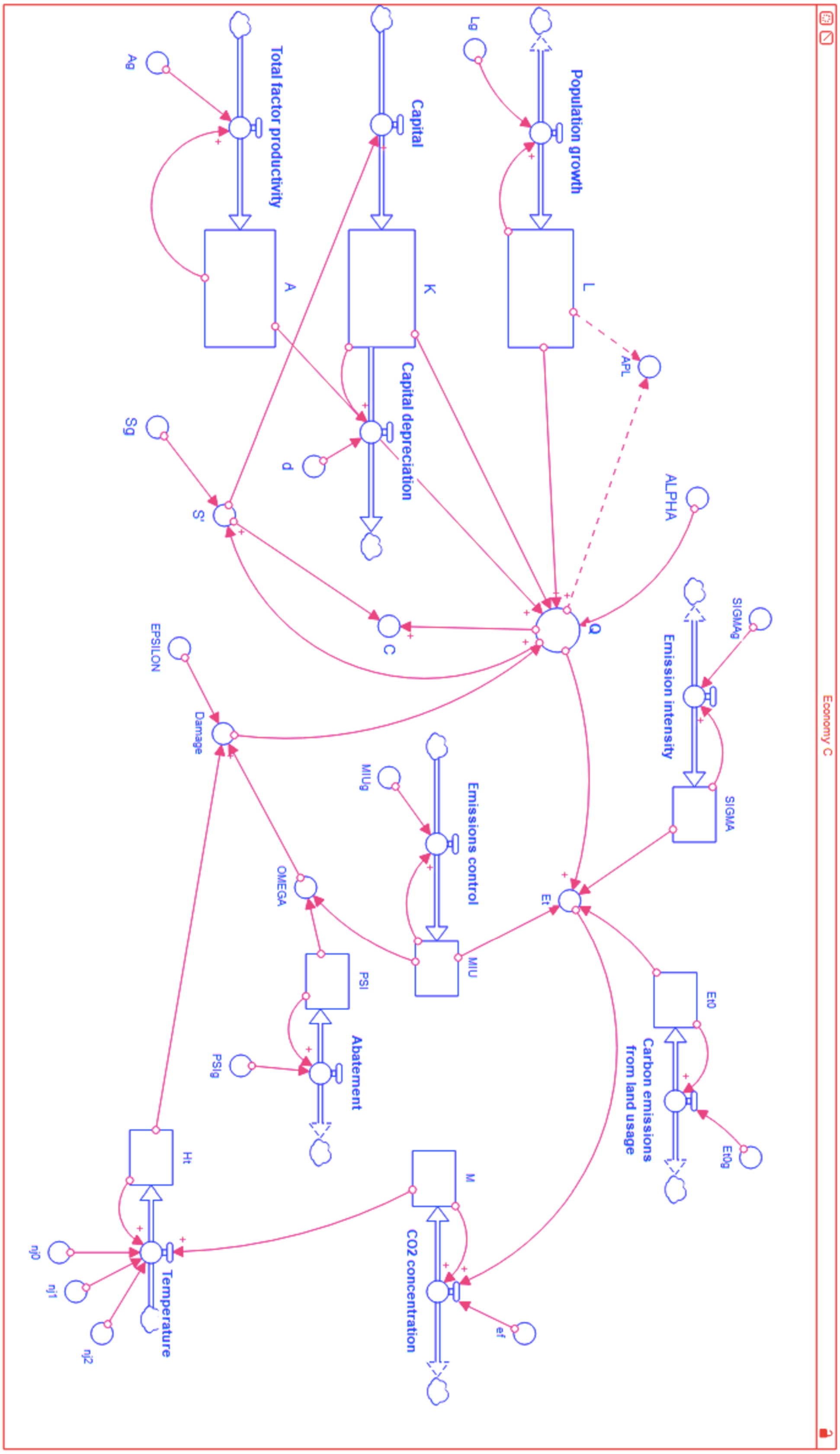
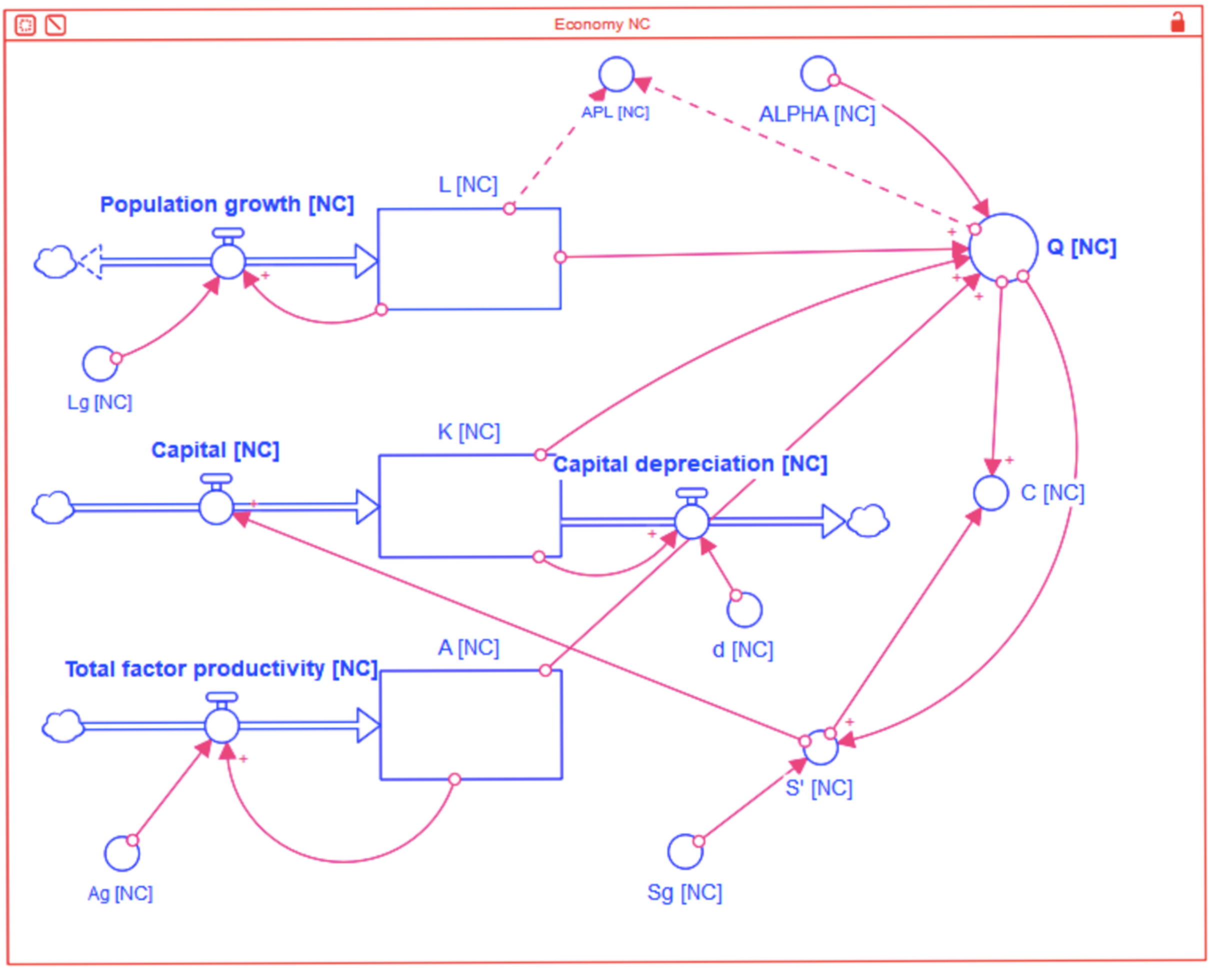
11 Appendices

Appendix A. Preview of the model of economy C



Appendix B. Preview of the model of economy NC



Appendix C. Equations and variables of the model

```
**********
Economy_C:
**********
A(t) = A(t - dt) + (Total_factor_productivity) * dt {NON-
NEGATIVE}
    INIT A = 5,115
    INFLOWS:
        Total_factor_productivity = -A+Ag*A {UNIFLOW}
Ag = 1,067
    INIT Ag = 0,01
ALPHA = 0,3
APL = Q/L
    UNITS: Trillion USD
C = Q-S'
    UNITS: Triillion US Dollars
    DOCUMENT: Total consumption
d = 0,1
Damage = (1-OMEGA)/(1+EPSILON*Ht^2)
    DOCUMENT: Numerator represents abatement, denominator
represents damage
phi = 1,013
    DOCUMENT: originally 0,9942
EPSILON = 0,00265
Et = (SIGMA*(1-MIU)*Q)+Et0
    UNITS: GTCO2 per Year
    DOCUMENT: Total CO2 emission
Et0(t) = Et0(t - dt) + (Carbon_emissions_from_land_usage) * dt
{NON-NEGATIVE}
    INIT Et0 = 2,6
    UNITS: GTCO2 per year
    INFLOWS:
        Carbon_emissions_from_land_usage = -Et0+(Et0*Et0g)
            UNITS: GTCO2 per year/Years
Et0g =  0,885
```

```
Ht(t) = Ht(t - dt) + (Temperature) * dt {NON-NEGATIVE}
    INIT Ht = 0,85
    UNITS: Degrees C increase from 1900
    DOCUMENT: Global mean surface temperature
    INFLOWS:
        Temperature = -Ht+(nj0+nj1*Ht+nj2*LN(M)) {UNIFLOW}
            UNITS: Degrees C increase from 1900/Years
K(t) = K(t - dt) + (Capital - Capital_depreciation) * dt {NON-
NEGATIVE}
    INIT K = 223
    UNITS: Trillion USD
    INFLOWS:
        Capital = S' {UNIFLOW}
            UNITS: Trillion USD/Years
    OUTFLOWS:
        Capital_depreciation = d*K {UNIFLOW}
            UNITS: Trillion USD/Years
L(t) = L(t - dt) + (Population_growth) * dt {NON-NEGATIVE}
    INIT L = 7,5
    UNITS: Billion People
    DOCUMENT: Population
    INFLOWS:
        Population_growth = -L+Lg+L
            UNITS: Billion People/Years
Lg = 0,21566
    DOCUMENT: Growth of population per half decade
M(t) = M(t - dt) + (CO2_concentration) * dt {NON-NEGATIVE}
    INIT M = 851
    UNITS: GtC from 1750
    DOCUMENT: CO2 concentration increase in the atmosphere
    INFLOWS:
        CO2_concentration = -M+phi*M+Et
            UNITS: GtC from 1750/Years
MIU(t) = MIU(t - dt) + (Emissions_control) * dt {NON-NEGATIVE}
    INIT MIU = 0,02988251
    INFLOWS:
```

```
        Emissions_control = -MIU+MIUg*MIU {UNIFLOW}
MIUg = 1,080805763
nj0 = -2,8672
nj1 = 0,8954
nj2 = 0,4622
OMEGA = PSI*MIU^2
    DOCUMENT: Fraction of Q spent on abatement
PSI(t) = PSI(t - dt) + (Abatement) * dt {NON-NEGATIVE}
    INIT PSI = 0,06696572
    DOCUMENT: Abatement cost function coefficient
    INFLOWS:
        Abatement = -PSI+PSI*PSIg
PSIg = 0,906493072
Q = (A*(K^ALPHA)*(L^(1-ALPHA)))*Damage
    UNITS: Trillion USD
    DOCUMENT: World gross output
S' = Sg*Q
    UNITS: Trillion USD
Sg = 0,22
SIGMA(t) = SIGMA(t - dt) + (Emission_intensity) * dt {NON-
NEGATIVE}
    INIT SIGMA = 0,3503200274
    INFLOWS:
        Emission_intensity = (-SIGMA+SIGMAg*SIGMA)
SIGMAg = 0,9277

**********
Economy_NC:
**********
"A_[NC]"(t) = "A_[NC]"(t - dt) +
("Total_factor_productivity_[NC]") * dt {NON-NEGATIVE}
    INIT "A_[NC]" = 5,115
    INFLOWS:
        "Total_factor_productivity_[NC]" = -
"A_[NC]"+"Ag_[NC]"*"A_[NC]" {UNIFLOW}
"Ag_[NC]" = 1,067
```

```
    INIT "Ag_[NC]" = 0,01
"ALPHA_[NC]" = 0,3
"APL_[NC]" = "Q_[NC]"/"L_[NC]"
    UNITS: Trillion USD
"C_[NC]" = "Q_[NC]"-"S'_[NC]"
    UNITS: Triillion US Dollars
    DOCUMENT: Total consumption
"d_[NC]" = 0,1
"K_[NC]"(t) = "K_[NC]"(t - dt) + ("Capital_[NC]" -
"Capital_depreciation_[NC]") * dt {NON-NEGATIVE}
    INIT "K_[NC]" = 223
    UNITS: Trillion USD
    INFLOWS:
        "Capital_[NC]" = "S'_[NC]" {UNIFLOW}
            UNITS: Trillion USD/Years
    OUTFLOWS:
        "Capital_depreciation_[NC]" = "d_[NC]"*"K_[NC]"
{UNIFLOW}
            UNITS: Trillion USD/Years
"L_[NC]"(t) = "L_[NC]"(t - dt) + ("Population_growth_[NC]") *
dt {NON-NEGATIVE}
    INIT "L_[NC]" = 7,5
    UNITS: Billion People
    DOCUMENT: Population
    INFLOWS:
        "Population_growth_[NC]" = -
"L_[NC]"+"Lg_[NC]"+"L_[NC]"
            UNITS: Billion People/Years
"Lg_[NC]" = 0,21566
    DOCUMENT: Growth of population per half decade
"Q_[NC]" = ("A_[NC]"*("K_[NC]"^"ALPHA_[NC]")*("L_[NC]"^(1-
"ALPHA_[NC]")))
    UNITS: Trillion USD
    DOCUMENT: World gross output
"S'_[NC]" = "Sg_[NC]"*"Q_[NC]"
    UNITS: Trillion USD
```

```
"Sg_[NC]" = 0,22
{ The model has 56 (56) variables (array expansion in parens).
  In root model and 0 additional modules with 2 sectors.
  Stocks: 12 (12) Flows: 14 (14) Converters: 30 (30)
  Constants: 19 (19) Equations: 25 (25) Graphicals: 0 (0)
  }
```

Univerzita Hradec Králové
Fakulta informatiky a managementu

Zadání bakalářské práce

Autor: **Roman Bakhta**

Studium: I1800530

Studijní program: B6208 Ekonomika a management

Studijní obor: Finanční management

Název bakalářské práce: **Simple DICE model**

Název bakalářské práce AJ: Simple DICE model

Cíl, metody, literatura, předpoklady:

1. Introduction - Climate change and its implications, relationship to economic growth

2. Method

- System dynamics usage for economic modeling
- Neoclassical model of economic growth
- Climate in economic modelling (DICE and other models)

3. Solow-Swan growth model implementation with the inclusion of climate module (DICE) in software Stella - model description, scheme, equations and parametrisation

4. Sensitivity analysis based on climate submodel parameters variation - influence on model dynamics

5. Conclusion

John D. Sterman, Business Dynamics: Systems Thinking and Modeling for a Complex World, McGraw-Hill Education, 2000
Radzicki M.J. (2009) System Dynamics and Its Contribution to Economics and Economic Modeling. In: Meyers R. (eds) Complex Systems in Finance and Econometrics. Springer, New York, NY

William D. Nordhaus, 1992. "The 'DICE' Model: Background and Structure of a Dynamic Integrated Climate-Economy Model of the Economics of Global Warming," Cowles Foundation Discussion Papers 1009, Cowles Foundation for Research in Economics, Yale University.

Zadávající pracoviště: Katedra ekonomie,
Fakulta informatiky a managementu

Vedoucí práce: Ing. Lukáš Režný, Ph.D.

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