SD Economic Model with Fossil and Renewable Energy[1]

PAWEL BARTOSZCZUK

Systems Research Institute, Warsaw, Poland

Abstract. *Our objective is to foster the understanding of the economic impact on environment. We apply SD modelling methodology and conduct our simulation. We investigate major trends of global threats: deteriorating environment and depletion of non-renewable resources. We list the important and causal relationships among the levels and trace the feedback loop structures. In describing an economic and environmental model we focus on the relationship among income, pollution, and non-renewable. This paper yields insight into the possibilities for replacing non- renewable fossil fuels with more renewable ones. Next, we present the simulation runs of the model, conducted with the help of existing system dynamics modelling tools.*

Keywords: *economic model, environmental systems, non-renewable resources, simulation*

1. Introduction

With the increasing interest in developing sustainable solutions to the world problems, including worsening of global environment and fluctuating economic conditions, the need for methods of predicting the outcomes of policies decision becomes more urgent. In the case of complex ecological-economic structures, experimental methods are frequently not possible, therefore representative methods can be very useful. This paper examines the possible impact of economic development on environmental quality. Certain plausible assumptions about the response of some variables are made. Although we have applied technological progress, different scenarios are possible, including irreversible decrease of non-renewable resources. The paper consists of 5 chapters. We present opinions on the influence of economic development on environment, with the stress on the Club of Rome ideas in the chapter 2. In chapter 3 we describe relations in our model and in chapter 4 and 5 present the results of our simulations and conclusion.

2. The different opinions about growth influence on environment

Nowadays numerous authors suggest that in the debate over economic impact on the environment, we have two perspectives: optimistic and pessimistic. Proponents of optimistic view argue that as resource are being depleted, the economy will substitute other more plentiful resources in place of scarce resource. Continued economic growth will produce less polluted, and more resource rich world (Ophardt, 1997). Beckermann (1999) claims that growth is beneficial due to supporting social improvement. Stiglitz (1996) suggest that the elasticity of substitution between two inputs: capital and resources is sufficiently large with new technologies. Lovejoy (1996) suggests that technology can change substitution over time so there is less scarcity. Mikesell (1995) emphasizes the lack of evidence that growth leads to lower productivity.

Some other research indicates that for a specific kinds of environmental problems the relation between income and the level of environmental pressure shows an inverted U curve (Arrow, at al. 1995; de Bruyn and Heintz, 1999; Dinda, 2001; Grossman and Krueger, 1995). According to those research, as development proceeds, pollution increases rapidly. At higher levels of development, structural changes lead to a decrease in pollution. Economic growth eventually redresses the environmental impact of the early stages of economic development, and that growth leads to further environmental improvements in developed countries or tends to fix environmental problems. The conclusion of those studies can be criticized on several grounds. Results obtained from cross-section data cannot be translated to future time-series for specific countries. Moreover, empirical studies only focus on particular aspects of environmental pressure not related to the carrying capacity natural resilience of ecosystems.

Optimism characterize many individuals, who believe that we have solved environmental problems in the past, so we will tackle them in the future. Overall, optimists view two things: (1) the elasticity of substitution between an essential resource and capital is greater than 1, and (2) technology will increase the productivity of resources faster than their exhaustion. The empirical literature provides a mixed and partial picture. While some studies yield substitution elasticities greater than unity (a necessary condition for economic growth models to generate sustainable paths) for metal: steel, copper and aluminium (Brown and Field, 1979), others suggest that for scarce materials like beryllium and titanium elasticity is close to zero (Deadman and Turner, 1988).

Pessimists claim that sustainability recognizes that without intervention the global environment will not be able to to provide a reasonable standard of living (Helm, 2000). If present economic growth tendency persist, the world will become more polluted and the supply of certain essential resources decline and they can be lost for ever with no

---

[1] This paper was presented at System Dynamics Conference, Nijmegen 22-28 July 2006

substitutes. The laws of nature demand that any substitution possibility must have declining elasticity (Reynolds, 1999). Malthus (cited by Solow (2000)), was the first who pointed out the possibility of growing relative scarcity of natural resources. The authors 'The Limits to Growth' Report continue to argue that economic growth must be lowered along with other changes (Meadows, 1972).

Meadows et al. (1972) concluded that if the present growth trends in world population, industrialisation, pollution, food production and depletion of non-renewable resources will be the same in future, the limits to growth will be reached sometime within 100 years. The limits to growth fairly and coolly interpreted is that there are limits to growth of material throughput for the international system. The major concern was entirely focused on what the world might look like. There was not one sentence or even a single word written about an oil shortage, or limit to any specific resource, by the year 2000. 'Limits to growth' are conditional warning, that without significant reductions in throughput over time, substantial declines in per capita food output, energy use and industrial production can be expected. Then, world population would be curtailed as a result of an increase in the death-rate caused by food shortages and environmental pollution. The Report predicted not only food crisis, but also natural resources exhaustion and environmental degradation caused by wastes. Also, it indicated that, if this exponential growth was not curbed, industrialization might lead to slow down of economic growth (Meadows, 1972). The analyse in the report did not include the rational response of an economic agent. However, they did draw public awareness to the need for saving and conserving the environment and natural resources (Hayami, 1997).

According to the Report, human use of many essential resources and generation of many kinds of pollutants have already surpassed rates that are physically sustainable. This decline is not inevitable. To avoid such decline, comprehensive revision of existing policies in rational consumption is necessary. Finally, building a sustainable society is still possible. Such society is much more different than society which tries to solve its problems by constant expansion. The emphasis on sufficiency, equity and quality of life rather than quantity of output is necessary. The transition to a sustainable society requires a careful balance among those values.

Club of Rome Report emphasised the examples of exponential growth: world population has been growing exponentially since the beginning of industrial revolution. In 1991 annual growth rate was estimated as 1.7%, which means a doubling time of 40 years. Also world production, relative to the base of 1963 year show clear exponential increase, as well. The concentration of carbon dioxide in the atmosphere has risen from 290 parts per million in the last century to over 350 parts per million and will continue on its exponential growth path. According to Intergovernmental Panel on Climate Change (IPCC), atmospheric CO_2 concentrations by 2100 will be in the range of 650 to 970 ppm. The increased atmospheric concentrations of CO_2 and other greenhouse gases (GHG) trap more of the earth's heat, causing temperatures to rise. As a result, it is predicted that the global average surface temperature can rise between 1.4 and 5.8 degrees Celsius between 1990 and 2100, an unprecedented rate of increase. These in turn are responsible for melting ice, rising sea levels, and a greater number of more destructive storms.

Growth can solve some problems, but it will create other and cannot continue forever (Meadows, 1972). Important constraints to growth are limits to the flows of energy and materials needed to keep people, cars, and buildings functioning. Many crucial sources are declining and sinks are overflowing. The throughput flows that preserve the human economy cannot be maintained.

Population and capital are engines of growth in the industrialised world. They both draw materials and most forms of energy from the earth and return wastes and heat to the earth. There is flow from sources to sinks, and limits to the rates at which human population and capital can use materials and energy, and there are limits to the rates at which pollutants can be emitted without harm to people. Herman Daly (1996) suggested that renewable resources should be used in amount no greater than the rate of regeneration. Non-renewable resources cannot be used more than the rate at which they can be substituted. The sustainable rate of emissions can be no greater than the rate at which pollutant can be recycled, absorbed or rendered harmless by the environment.

Moreover, according to the Report’s authors, food production, resource use and pollution tend to increase exponentially not because they multiply themselves, but because population and capital drive them. Most economic growth takes place in the already industrialised countries. Economic growth systematically continues to occur rather more in the rich countries. It is much easier for rich populations to save, invest, and multiply their capital than for poor to do the same. Simply, they have larger stock of capital. Basic needs are met, so they can save some capital. Poverty keep people in conditions where they have no education, no health care, no hope.

Brown (2001) point out that treating the environment as part of the economy has produced an economy that is destroying its natural support systems. He notes that if China follow American consumption style and every family have car, it would need 80 milion barrels of oil a day, more than current world production. He is optimistic and show how to change the economy. In the new economy, wind farms replace coal mines, hydrogen-powered fuel cells replace internal combustion engines and cities are designed for people, not for cars.

3. The model

Economic and ecological systems can be depicted as a collection of inter-related items, like stocks and flows, internal feedback mechanisms, non-linearities, delays and uncertainties in system dynamics. First, we consider macroeconomic relations with capital, income, consumption, and savings, which can be found in many macroeconomic books (Solow, 2000). In the model we have two types of equations: one is a stock – low relationship that specifies a dynamic movement (Yamaguchi, 2001). Another one is equation of causal relationship in which change in one variable is caused by other variable and constants

$$K_{t+1} = K_t + I_t - D_t \tag{1}$$

$$D_t = \delta K_t \tag{2}$$

$$Y_t = A K_t^{\alpha} L_t^{1-\alpha} \tag{3}$$

$$c_{p_t} = \min(c_s, \frac{Y_t}{N_t}) \tag{4}$$

$$C_t = c_p N_{t,,} \tag{5}$$

$$S_t = Y_t - C_t \tag{6}$$

$$S_t = I_t \tag{7}$$

$$N_{t+1} = N_t + \Delta N_t \tag{8}$$

$$\Delta N_t = \alpha N_t - \mathrm{B} N_t \tag{9}$$

$$L_t = \tau k N_t \tag{10}$$

$$R_{t+1} \equiv R_t - \Delta R_t \tag{11}$$

$$\Delta R_t = \lambda Y_t \tag{12}$$

$$\lambda = (1 + r)^{-t} \tag{13}$$

$$\Delta GI_t = \mu S_t \tag{14}$$

$$GK_{t+1} = GK_t + \Delta GI_t - \Delta GD_t \tag{15}$$

$$\Delta GD_t = \pi \, GK_t \tag{16}$$

$$S_{t+1} \equiv S_t + \Delta S_t \tag{17}$$

$$W_t = \varphi \, Y_t \tag{18}$$

where:

K_{t+1}- capital stock over time t+1, K_t- capital stock over time t, I_t- is investment over time t, D_t- capital depreciation over time t, δ - depreciation rate, Y_t- income over time t, A-technological factor, L_t –labour, C_t-total consumption over period t, c_p- consumption per capita over period t, N_t - population over time t., S_t- savings over time t, N_{t+1} - population over time $t+1$, t-time, ΔN_t - net birth, α -birth rate, B-death rate, τ-fraction of productive age people, k-is fraction of employed in the productive age population,. R_{t+1}- non-renewable fossil fuels over time period t+1, R_t- non-renewable resources over time period t, ΔR_t - non-renewable resource depletion, λ- is input amount of fossil fuels necessary for producing an unit of output, r- is technological factor, ΔGI_t -amount of renewable substitutes (green investment), μ - the level of substitutes, ΔGD_t -depreciation of green capital), π- coefficient of green capital depreciation, S_{t+1}- is sink of pollutants and garbage over time t+1, S_t- is sink of pollutants and garbage over time t, W_t –is amount of industrial wastes created during producing a unit of output, φ- is coefficient of industrial wastes,

Those equations become simple enough to describe the growth process of our economy. Equation (1) represents a capital accumulation process in which capital stock is increased by the amount of investment and decreased by depreciation in a specified time unit, like one year. Equation (2) represents capital depreciation. Relation (3) is well known by economists as a production function. We assume all production comes about as a function of capital and labour. The amount of total and per capita consumption is presented in equations (4)-(5). The consumption per capita is miniumum from income per capita and substantial level of consumption.

Subtracting consumption from income leaves savings, (6). In our case 20 percent of consumption is saved and invested. Saving can be changed into investments goods like raw materials, thereby increasing capital stock. At equilibrium, investments have to be equal to saving as shown in (7), otherwise output would not be sold out completely or would be in short supply. With the introduction of a delayed consumption function that is demanded irrespective of the output level, the amount of saving defined in the saving function might become negative, as population and consumption increase. To warrant a non-negative amount of saving, the saving function should be defined as maximum from zero and as the difference between output and consumption.

Each year the population is increased by the total number of births that year and decreased by the total number of deaths that that year, (8) -(9). Number of working force is proportional to the population, (10). Now we present some relations on the Figure 1.

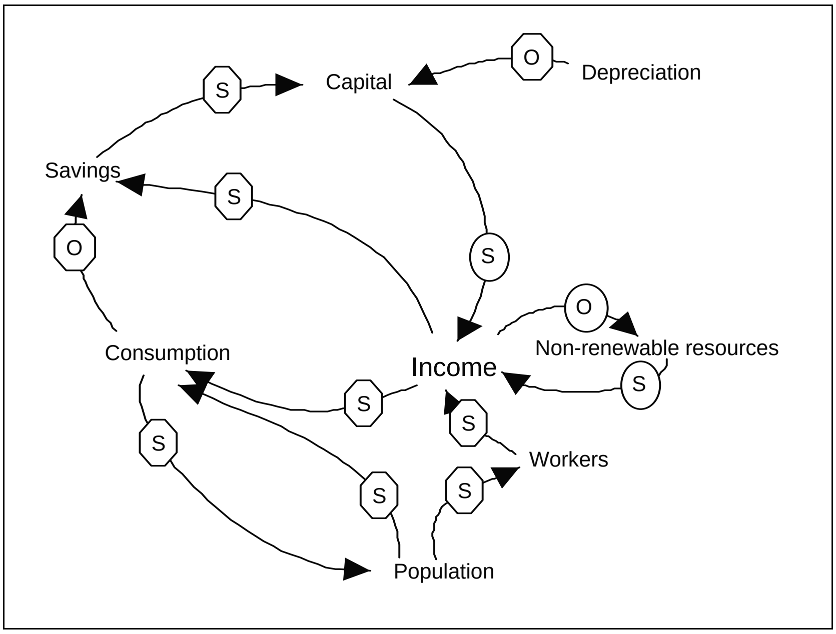

Figure 1.Diagram made in Powersim. Causal loop between capital, income, population, savings, nonrenewable reources (fossil fuels) and workers. *S*- change in the same direction and *O*- change in the opposite direction.

Next, we add to our model non-renewable fossil fuels, (11)-(13). As the world's population and capital grow, the demand for non-renewable resources will increase accordingly. The amount of resources (fossil fuels) consumed each year can be found by multiplying the output (income) by usage rate. As population becomes wealthier, it tends to consume more resources per person per year. Conversely, technological progress can lead to lower input of resources to production.

For simplicity, let us assume that non-renewable resources are represented by fossil-fuels such as coal, gas, and oil. Then, parameter λ is interpreted as an input amount of fossil fuels necessary for producing a unit of output. That input decreases with time due to application of new technologies enabling effective use of non-renewable resources. Depletion of non renewable resources depends on the demand for fossil fuels. In turn, demand for non renewable fossil fuels depends on demand for energy minus green energy generation. We assume, similarly to Yamaguchi (2001), that at least 10 percent of energy comes from energy generated from fossil fuels.

Let ΔG_t be an inflow amount of renewable substitutes (green investment) that can be added to the green capital stock, μ is the level of the substitutes, and ΔG_t is green depreciation (14)-(16). We assume, for simplicity, that the green investment are proportionate to the saving.

At present, let us assume that production and consumption activities, in addition to capital accumulation, generate as by-products consumer garbage, industrial wastes, and depreciation dumping. We assume these by-products are accumulated as an artificial environmental stock called sink, (17). These by-products are, in turn, dumped to the earth or they are scattered in the atmosphere. The amount of industrial wastes (mainly pollution) is proportionate to an income, (18).

4. The results of simulation.

We considered two possible scenarios of development. In first-pessimistic scenario we assume that at least 50% of energy comes from nonrenewable resources, and the rest from renewable. In the second scenario this percentage is at least 10%, what means more green energy generated. The results of first scenario simulations show that in the coming decades we can expect decrease in nonrenewable resources. Green energy declines after initial increase, due to lack of investments and savings (green energy is proportional to the savings) Population decreases due to lower output, which is available for consumption. Capital is lower due to lack of investments after 2200 year. In second-more optimistic scenario, we have increase in energy use, industrial production, capital, investments and in population. The simulation shows an initial increase of output (income) (Figure 2). At the outset, the fossil fuels are depleted at the rate of 0.45% per year . Population is declining after initial increase, but at the end of our simulation, around 2500 year, it increases again. Carbon in atmosphere declines due to commonly applied green energy.

Economic growth leads not only to the depletion of renewable resources, but also to increase of pollution and wastes. In the model, we allow for the non-renewable resources to be partly substituted by green capital, from 2016 year, but even with that energy our resources are depleted. This result is a bit surprising, but we must remember that the amount of green energy is a proportional to the savings. Since the savings are lowered as a result of lower economic output, renewable resources will be depleted when consumption is bigger than zero.

Population is increasing over the period of our simulation. Consumption or erosion of the carrying capacity by the population could create a negative feedback, which will limit growth in a longer future. When resources over period of our simulation are ample, positive growth dominates and the system grows exponentially. As the economy grows, resources are more depleted. In the future the negative loop gradually can gain in strength. At some point, output, consumption, and population could fall.

5. Conclusion

The results of simulation support view that growth can lead to the exhaustion of natural resources and deterioration in the environment. A depletion of non-renewable resources decreases output and lead consequently to a decrease in population. To diminish depletion of resources, an efficient use of resources has to be created. We can circumvent such depletion of non-renewable resources and stay within a limit of resource availability by limitating the inefficient use of fossil-fuels.

To accomplish this circumvention, an introduction of long-term management resources is necessary. Particular interest should be put on the influence of technological progress on effective consumption of non-renewable resources and productivity of production factors. It is essential to implement renewable sources of energy, like biomass instead of fossil fuels, together with less capital-consuming technology. To accomplish this goal, we have to develop new modern technologies.

A constructed system dynamics model is very comprehensive. The greatest value of the model is not in exact prediction and forecasting, but developing our basic understanding of the relationships between economy and the environment.

References

Meadows, H. D., et al. (1972), *'The Limits to Growth. A report for the Club of Rome's'. project on the predicament of mankind*, Universe Books, New York.

Arrow, K. et al. (1995), 'Economic growth, carrying capacity and the environment'. *Science*, Vol. 268, pp. 520-521, reprinted in *Ecological Economics,* Vol.15, pp. 91-95.

Beckermann W. (1999), ‘A pro-growth perspective’, in: Handbook of environmental and resource economics, ed. J. C. J.M van den Bergh, Edward Elgar, Cheltenham UK, Northampton MA, USA

Brown G. M. and B. Field, (1979), ‘The adequacy of measures for signalling the scarcity of natural resources’, in U.K Smith (ed.), Scarcity and Growth Reconsidered, Baltimore, MD: Johns Hopkins University Press, pp. 218-248

De Bruyn S. M. and R.J. Heintz, (1999), ‘The environmental Kuznets Curve hypothesis, in: Handbook of environmental and resource economics’, ed. J. C. J.M van den Bergh, Edward Elgar, Cheltenham UK, Northampton MA, USA

Daly, E.H. (1996), ‘*Beyond growth’*, Beacon Press, Boston.

Deadman D. and R.K. Turner (1988), ‘Resource conservation sustainability and technical change’, in RK Turner (ed.), Sustainable Environmental Management: Principles and Practise, London : Belhaven Press, pp. 67-100.

Dinda, S., Coondoo, D. and M. Pal (2000), ‘Air quality and economic growth: an empirical study’, *Ecological Economics*, Vol. 34, pp. 409-423.

Grossman, G. M., Kreuger, A. (1995), ‘Economic Growth and the Environment’, *Quarterly Journal of Economics*, Vol. 110, No. 2, pp. 353-377.

Hayami, Y. (1997), ‘*Development economics from the poverty to the wealth of nations’*, Clarendon Press, Oxford, England.

Helm, D. (2000), ‘Objectives, Instruments and Institutions’ in Environmental Policy’, Oxford: Oxford University Press

Lovejoy, D., (1996), ‘Limits to growth*?’, Science and Society 60 (3), 266-278.*

Mikesell R.F. (1995), ‘The limits to growth a reppraisal’, *Resources Policy* 21 (2), 127-131.

Ophardt C. (1997), **‘**Human society and environmental impacts global collapse or sustainable future ?’ (http://www.elmhurst.edu/~chm/onlcourse/chm110/labs/limits.html)

Solow, R. (2000), ‘*Growth theory. An exposition’,* Oxford University Press, Oxford.

Stiglitz, J.E, (1979) ‘A neoclasical analysis of the economics of natural resources’. In: Smith, V.K. (Ed.), Scarcity and growth reconsidered. Resources for the future, Baltimore, pp. 36-66.

Woodwell J.C (1998), ‘*A simulation model to illustrate feedbacks among resource consumption, production and factors of production in ecological-economic systems’, Ecological Modelling, 112,* 227-247

Yamuguchi, K. (2001), ‘*A step-by step system dynamics modeling of sustainability*’. in: Proc. of International Conference of the System Dynamics Society, Atlanta, US.