Study on the Club of Rome's World3 Model

Project Introduction to Computational Science 2014
University of Amsterdam

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Introduction

This report describes the modelling and simulation project for the course Introduction to Computational Science of the college year 2014-2015 at the University of Amsterdam. The aim of the project is to perform a science project, which will be supported by a simulation study.

We will investigate the Club of Rome's World3 model, which models interactions between industrial growth, population, food production and pollution on a global scale.

Background of the model and its use

In 1968, a group of people from politics, business and science came together to *"discuss the dilemma of prevailing short-term thinking in international affairs and, in particular, the concerns regarding unlimited resource consumption in an increasingly interdependent world"*. This group was named *The Club of Rome*, after the location of the meeting. The first and subsequent meetings resulted in the book '*Limits to Growth*', published in 1972. In the book it was predicted that economic growth could not continue indefinitely, mainly because of the limited availability of natural resources and emissions. Somewhere in the twenty-first century, the growth would end in a uncontrolled decline in population and human welfare.

The model used in the study is called the World3 model. It was the first model that used computer simulation to model the interactions of five submodels, which represent capital, natural resources, agriculture, population and pollution, on a global scale.

The World3 model is far from perfect and was merely a first step in modelling the global world. The authors point out the use of inadequate data, the usage of quantifications of factors for which the influence is not fully clear, such as pollution,

and unknown development of technology in the future. Also, natural resources are seen as one identity, while in reality substitutions of depleted natural resources are possible. Increasing prices because of scarcity and the stabilising working of the law of supply and demand are missing in the World3 model; very different from assumptions economists often make in their models.

Despite its flaws, the World3 model is suitable to illustrate the validity of the Club of Rome's hypotheses. The model is an example that it is not necessary to have a perfect model to give an clear insight in problems. The model does not give a prediction, but is sketching alternative scenario's for humanity. For taking appropriate measures to prevent a scenario becoming true, the model and its validity need to be studied and improved extensively. Nevertheless, the authors use the model "*to identify the future policies that may lead to a stable rather than an unstable behaviour mode*". The World3 model shows what possibly can go wrong. Vermeulen and De Jongh [1976] conclude that, while in *Limits to Growth* very severe measures are suggested for every subsector of the world model in order to avoid the catastrophic population collapse of the standard run, that by combining three changes of 10% each in the parameters ICOR, FIOAC, ALIC, the collapse of population can also be avoided. They speculate that the real world has so many variables and is so flexible that the correct small pressures on the correct parameters could cause desirable outcomes for the world's evolution.

Limits to Growth received a large amount of publicity at publication. Concerned governments nevertheless continued to go everything they could to stimulate economic growth and no start was made for a transition to a sustainable growth. This was mainly to reduce unemployment. Pestel [1988] believes that the main contribution of the report is that it led to a continued interest in future of humanity and the start of many discussions.

The difficulty of the problem is that no single country is responsible on its own or able to take appropriate actions. Measures on a world wide scale are necessary, which are very difficult to coordinate. The history of the ozone hole and acid rain shows that global coordination is not impossible. In this report, we will not elaborate on the subject of international cooperation.

Critics on the World3 model and Limits to Growth

The report and the model have received many critics. However, the conclusion remains strong: unlimited growth cannot continue. Some people argued that the equation $y(t) = ae^{rt}$ is also sufficient to show that sustainable growth cannot continue and that the model thus overcomplicates. Others criticize the model for its oversimplification in the aggregation of variables.

Economists often point out that the used assumptions in the models are very different from the axiom's economists often use. Also, the tone of the report is pessimistic. The Club of Rome was wrongfully called the zero growth movement, although the conclusion of the report does not to deny this qualification. In the report there is a dedicated chapter about the conditions to obtain sustainable growth and what growth in a global equilibrium means. Within these conditions, company's can rise and fall,

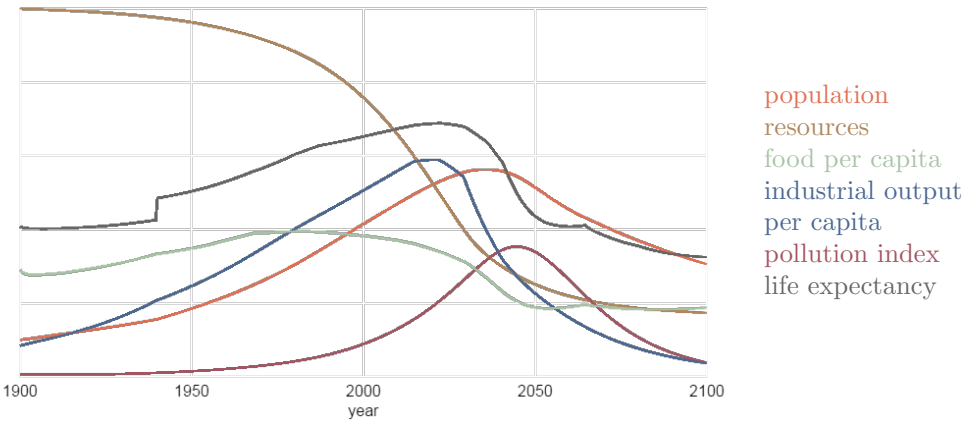

Figure 1: Behaviour of the model in the standard run

local population can grow and decline. Technological developments can improve the average standard of living.

Standard run of the model

Figure 1 shows the behaviour of the standard model, i.e. of the model when no changes to the standard parameters are made.

Note that the scale on the y-axis is missing. This is because the model does not give predictions, but a direction. The numbers are very likely to be inaccurate and are thus not of great importance.

The model shown in figure 1 shows that around 2040 society will collapse. This happens shortly after the industrial output drops. This manifestation of these catastrophes is an indication that not only the resources are depleted but also the pollution of this world is rising to a record high.

The rising pollution also has a big effect on the life expectancy of the population. Figure 1 shows a correlation around 2045, where pollution is at the largest peak and the life expectancy drops rapidly. Since the turn of a rising life expectancy to a dropping one, the population growth has stagnated, which results in a decay of the human population.

Research questions

A full analysis of the parameters of model, the influences of the submodels and making simplifications is enough to write a PhD thesis: see Thissen [1978]. However, we would like to study small parts of the model. Based on our own interests and the discussion

of the model in Limits to Growth, Thissen [1978] and Vermeulen and De Jongh [1976], we ask the following questions:

- What is the influence of the size of the population on the use of natural resources?
- Can the collapse of population indeed be prevented by increasing the variables ICOR (industrial capital-output ratio) and FIOAC (fraction of inputs allocated to consumption) by 10% and decreasing ALIC (average lifetime of industrial capital) by 10% in 1975?
- What is the influence of the amount of available natural resources?
- Do the conditions in the Limits to Growth to obtain sustainable growth indeed lead to a sustainable equilibrium?

Additionally, we will investigate behaviour of the model we find remarkable while varying parameters.

Implementation of the model

The World3 model is an example of a model in the System dynamics formulation, which is based on feedback loops. Figure 2 An overview of the model and the interactions between the submodels. We included this figure to give an impression of the size of the model, not for details.

The complete model consists of more than 150 differential equations and variables. The original model is formulated in a special programming language called DYNAMO. The model has since then be ported by the original authors to another language, called STELLA, and extended to include human welfare and footprint indicators. Many others have created ports of the DYNAMO formulation to other languages, such as Java (`http://www.world3simulator.org/`), Vensim (`http://models.metasd.com/tag/world3/`) and JavaScript (`http://bit-player.org/extras/limits/`).

As we wanted to learn how to implement such large model and see how the model really worked, we tried to implement the World3 in the formulation as described in Thissen [1978] in Python.

For solving the differential equations, we used Euler's method (first order). Let $\mathbf{X}(t)$ represent the vector with all state variables at time t, with $t = 0$ the initial state, and $\mathbf{f}(\mathbf{X}, t)$ the function expressing the rate of change for each state variable at time t, given the state $\mathbf{X}$. Then

$$\mathbf{X}(t) = \mathbf{X}(\mathbf{0}) + \int_0^t \mathbf{f}(\mathbf{X}, \tau) d\tau \tag{1}$$

can be approximated by the recursion

$$\mathbf{X}(t) = \mathbf{X}(t - dt) + \mathbf{f}(\mathbf{X}(t - dt), t - dt) dt, \tag{2}$$

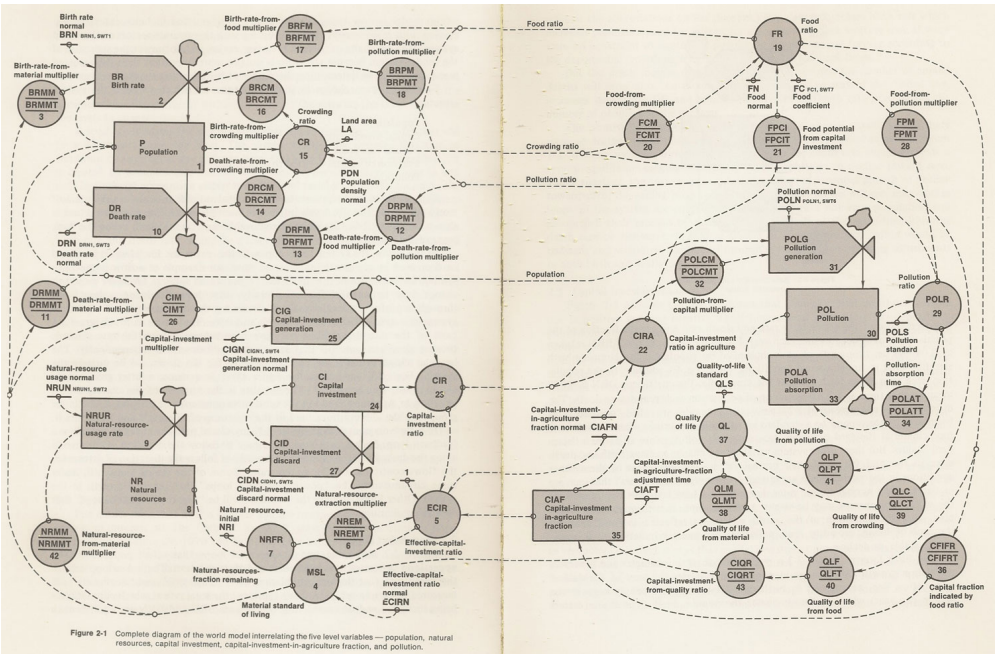

Figure 2: Diagram of the world model from Forrester [1973]

with dt the time step that should be taken sufficiently small. The standard value for dt used in the World3 model is $dt = 0.5$. In the World3 model, $t = 0$ represents the year 1900 and $t = 1$ 1901.

The World3 model consists of different submodels. In Thissen's formulation, the capital and resource subsectors are merged. The other models are the population, agriculture and pollution submodels. The interactions between these submodels can be seen in figure 3. Thissen omitted the job sector from World3, as this model proved to influence the model behaviour only under a few, very specific circumstances. Also, in his formulation three coupling variables between the models are expressed in total numbers instead of numbers per capita. These are the industrial output, service output and food production. In this way, the submodels could be investigated without having the population submodel. He chose to write down the World3's population model without age distribution, one of the three Meadows et al. [1974] provides.

Firstly, we implemented a simplified capital model. Thissen suggested that differences in neither population, agriculture or pollution has any major effect on the capital. This simplified model therefore uses constants for input of these submodels as an alternative.

As we thought this model was too easy we started to replace this simplified capital and resources model with the full model. This model relies on the three other submodels, which we needed to implement together. However, we did not succeed. We

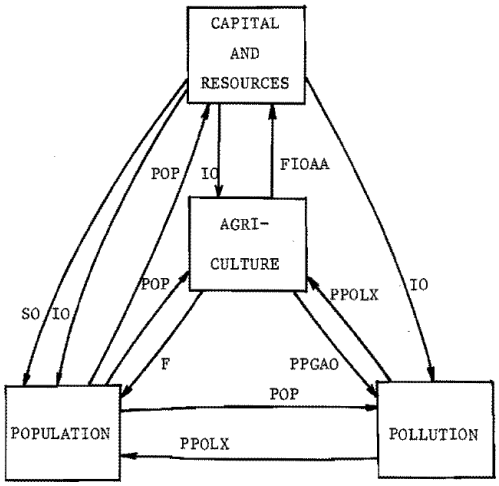

Figure 3: Interactions between the four submodels of World3, without job sector (Thissen [1978])

will discuss our problems and use one of the ported versions of others for an analysis of the model.

Simplified resource and capital model

We have successfully implemented the simplified resource and capital model from Thissen [1978] without problems. See the results for a comparison between the standard run and the simplified model.

Implementation of Thissen's full formulation

As will be shown in the results section, our implementation of Thissen's model also does not give correct results.

A particular problem we encountered at the implementation is the use of a function from DYNAMO called DELAY3. This function represents a third-order linear delay. Although this function is implemented in and documented for Vensim, we were not able to find an explanation we could understand.

To come up with a working model, we probably need to understand and implement the original model formulation from Forrester [1973] instead of the formulation from Thissen [1978]. DYNAMO is an old language, with the special feature that equations can be written down in any order. The compiler does reorder the equations automatically. We expect this to be very challenging to implement this in a sequential language as Python. After implementing the model in the sequential way, we discovered that the author of the JavaScript port also failed at implementing the model sequentially (Hayes [2012b]). Eventually, he mimicked the automatic ordering of equations of the

DYNAMO compiler in JavaScript. Although his source code can be studied, we are not fluent in JavaScript enough to understand his methods.

Unfortunately, we do not have access to the newer STELLA formulation.

Approaches taken to find the mistake

First, the model was thoroughly checked for typing errors. We corrected two or three, but this didn't lead to a working model.

Secondly, different interpretations for the DELAY3 function were implemented. As we think this function represents some kind of moving average, it is our hypothesis that replacing shouldn't have a large impact on the model. This didn't improve our models.

Thirdly, we modified the JavaScript port Hayes [2012b] to print the dependent variables for each submodel from figure 3 to study the differences in the change of variables after one iteration. In the first iteration, the submodels only depend on the initial values, of which we assume implemented them correctly. If only one of these values would be wrong, this would be due a mistake in the specific submodel of the variable. However, as can be seen in table 2, all variables differ. This leaves us clueless.

After one iteration the numbers in the JavaScript version differ in several orders of magnitude from the initial values, which are directly copied from the JavaScript source. Our values seem more probable, but our model is wrong and the JavaScript model isn't. Correcting for Thissen's warning that some values in the original model are per capita, does not lead to correct numbers. Again, this could be due our unfamiliarity with the JavaScript code, but printing is done by provided functions of the code.

Finally, at writing the report, we discovered that our simplified model didn't work correctly either. We compared an old version of the simplified model with the current version. It turned out that the old version was correct, but the current version turned out to be false. Our first guess was that the mistake was in the code, but by comparing the code line by line it showed no mistakes, math wise.

As we ran short on time we decided to cancel our hunt for the mistake, but our final guess would be that somehow certain variables are not set properly or calculated properly, mainly the initial values. Some initial values need to be calculated nonetheless and are therefore error prone. But by disabling the calculation and making it a constant it showed no significant changes. Therefore the variable saving within the model class should be looked into. This is very time consuming and because of it, skipped.

Results and analysis

Simplified capital and resources model

As stated earlier, this model uses constant input for population, agriculture and pollution on the whole time horizon from 1900 until 2100. Figure 4 shows that the simplified model closely resembles the corresponding variables in the JavaScript model. Note that scale on the y-axis does not matter. The numerical values correspondent. The

Variable	**Meaning**	**Initial value**	**Python**	**JavaScript**	**Units**
POP	Population	1.6e10	1.56e10	2.32e10	amount
IO	Industrial output	7.90e11	6.65e11	1.00e-3	dollars per person-year
SO	Service output	1.00e13	1.00e13	0.215	dollars per year
F	Food	-	1.72e12	7.48e12	kilograms per year
FIOAA	Fraction of industrial output allocated to agriculture	-	0.247	0.040	-
AI	Agricultural inputs	-	7.63e16	3.99e-6	dollars per year
FALM	Fraction of inputs allocated to land maintenance	0	0.040	0.052	-
PPOLX	Index of persistent pollution	1.36e8 (in 1970)	0.184	7.69e-16	dimensionless

Table 2: Values of inter-submodel variables in the standard model after one time step, with $dt = 0.5$

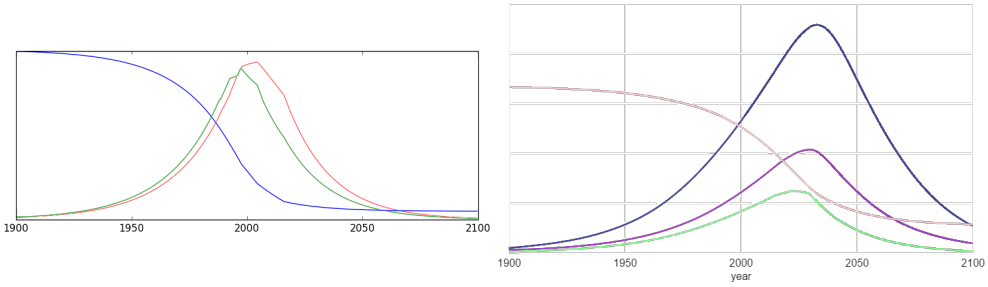

Figure 4: Left: simplified model in Python with $FIOAA = 0.05$ and the variables in the simplified model in the JavaScript model. Legend left: service capital , industrial capital, nonrenewable resources. Legend right: industrial capital, industrial output, nonrenewable resources, service capital

graph can be shifted by choosing $FIOAA$ (fraction of inputs allocated to agriculture) differently.

Our Python implementation

Figure 5 shows that our implementation of the full model is incorrect. The graph should be equal to the right graph of figure 4.

JavaScript model

To answer the research questions posed earlier, we modified the JavaScript port from Hayes [2012b]. The author warns that there are several more versatile and more trustworthy implementations available. Regardless, we decided to use only the JavaScript port due unavailability of source code or complete unfamiliarity with the used programming languages of other models.

When figure 6 is compared to figure 1, it can be seen that the decrease of the population is delayed when natural resources are increased. Industrial output attains a higher maximum and pollution rises drastically. One of the examples of the use of incorrect data was the amount of available natural resources. New techniques have made it, for example, possible to extract oil deeper from the earth. However, as we will see, this has no influence on the main conclusion of the report.

Figure 7 is a composition of several figures. First, it is shown that when the fraction of output consumed is lowered from the standard 0.43 to 0.01, industrial output grows enormously fast and population declines around 1960 because of pollution.

The second picture displays the behaviour of the model when the time step is changed to 2. This reminds us of the instability of the discrete Lotka Volterra model from the lectures.

In the third picture, the population is kept fixed from 1975. In the report Limits to Growth, this is done by setting the death rate equal to the birth rate. We did not succeed in doing this. Based on figure 2, the birth and death rate only have influence

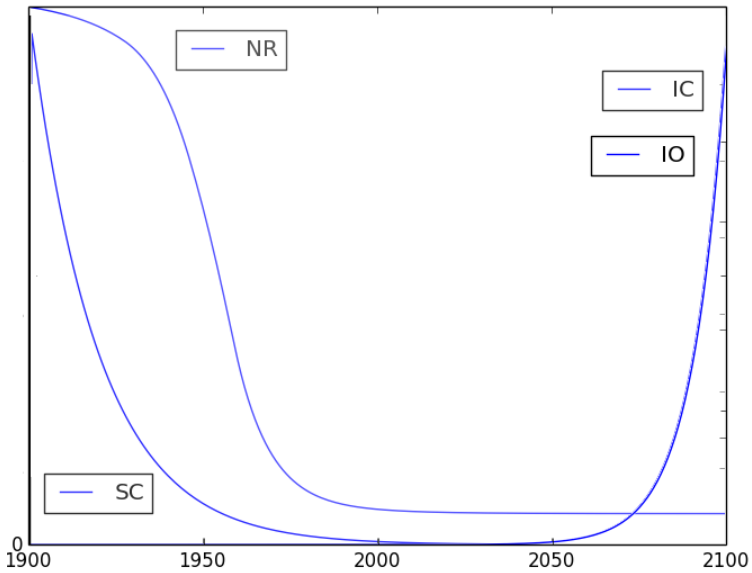

Figure 5: Incorrect implementation of Thissen's full model

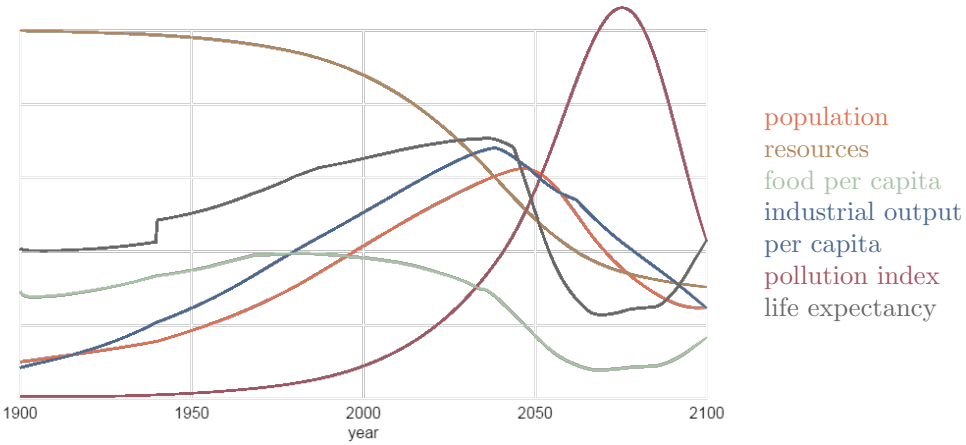

Figure 6: Behaviour of the model with twice the amount of available non renewable resources

on the other equations by the total population. This is why we kept the population from 1975 fixed. The resulting model has the same form as in the Limits to Growth report, but seems shifted to the right. The axis in Limits to Growth is not very clear. It demonstrates that only keeping the population at a fixed level is not enough for an equilibrium, because of a large increase in industrial output, food production and service output (not shown in our picture). Keeping the population fixed does not have any influence on the the depletion of natural resources.

For the fourth picture, the measures suggested by Vermeulen and De Jongh [1976] are implemented. This shows the decrease in population is only delayed to after 2100 and not prevented.

The last two pictures in figure 7 represent the behaviour with the fraction of consumed output 0.51 and 0.52. Changing this parameter by such small amount causes a major difference in. Unfortunately, the model doesn't support the human welfare index of newer versions of the World3 model.

To investigate the phenomenon that caused the drastic increase in life expectancy around the Second World War, we printed the values of the life expectancy and the components it is computed from in time. It appeared that in 1940 the life time multiplier from health services increased. The code showed a hard coded policy change in this year, so we went on to investigate why. In Meadows et al. [1974] it is described that the advances in technology caused a major increase in life expectancy from 1900 until 1966. It was chosen to implement this by a simple shift from the postulated 1900 table function to the 1966 in 1940. We did not notice this at implementing the Python model, as Thissen does not make this distinction.

The Club of Rome today

Today, the Club of Rome still exists. The focus in its early years was on the nature of the global problems and on new pathways for world development. Currently, the Club of Rome defines and communicates the elements of a new economy, which produces real wealth and well-being, without degrading natural resources and and with providing meaningful jobs and sufficient income for all people. Updates of the report are published every 10 years and confirm the urgency of the problems we are facing.

Conclusion

The World3 model and Limits to Growth discusses interesting and urgent problems. A full analysis of the model has proven to be enough work for a PhD thesis, i.e. more time than we have for this assignment. Unfortunately, we haven't succeed to implement the World3 model in Python. However, we learned a lot at implementing and investigating the model.

As for which "dynamic tendencies", as it is called in the Limits to Growth, will indicate how the future is going to be, is not yet clear. We are currently at the peak of welfare predicted by the model. Some scientists are optimistic about the ability to

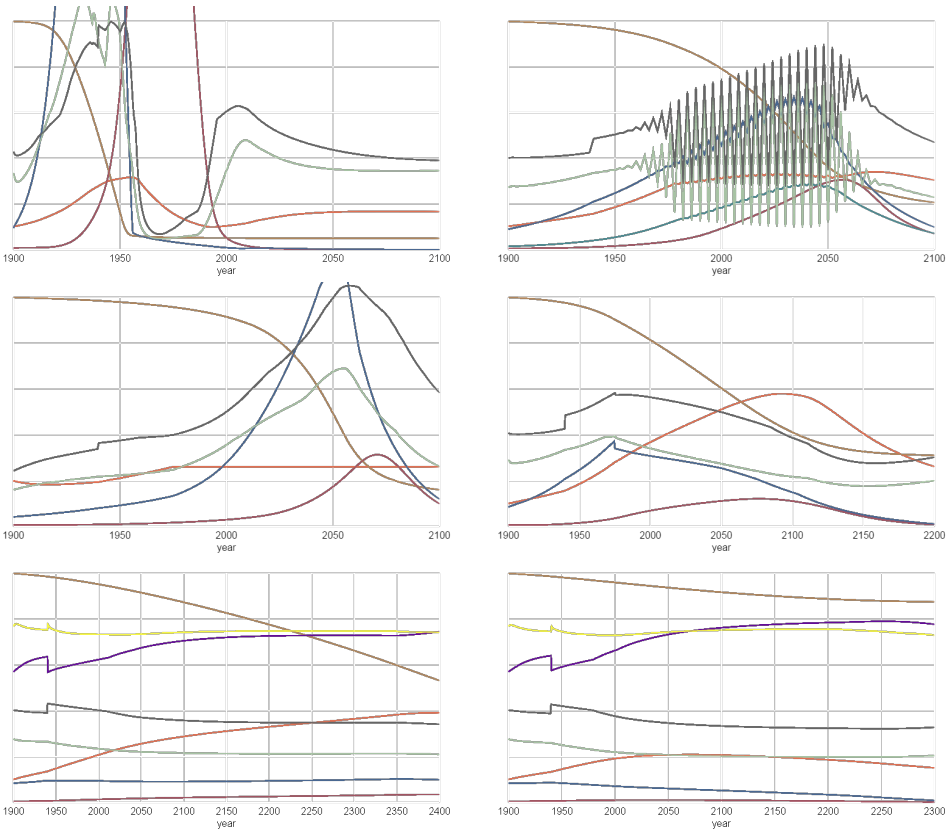

Figure 7: Left to right, upper to lower: standard run with the fraction of output consumed 0.01, standard run with $dt = 2$, standard model with fixed population from 1975, standard run with fraction of output 0.51 and standard run with fraction of output 0.52

deal with the issues before the world collapses, while others are not. The consequences of an overshoot are already observable, such as in global warming.

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