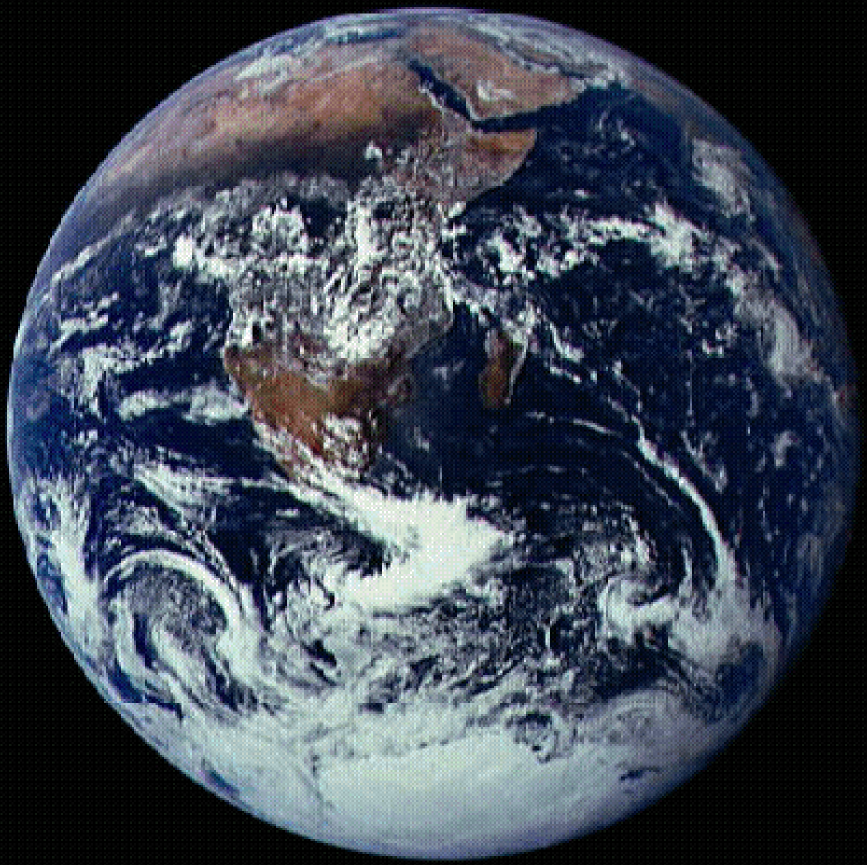
World Dynamics



In this lecture, we shall apply the ***system dynamics*** modeling methodology to the problem of making predictions about the future of our planet.

This has been one of the most spectacular --and also most controversial-- of all applications of this methodology reported to this day.

Table of Contents

Forrester's World Model

- In 1971, ***J.W. Forrester*** published a model, that he had developed for the ***Club of Rome***, offering predictions about the future of our planet.
- The model makes use of his ***system dynamics*** modeling methodology.
- It is an extremely simple ***5th-order differential equation model***.
- He sold immediately several million copies of his book, which was also quickly translated into many languages.
- He was strongly criticized for his model by many of his colleagues.

Selection of State Variables I

- Which variables should be used as state variables? How many of those are needed?
- There obviously is ***no good answer*** to these questions. It takes either genius or recklessness to even come up with a ***meaningful answer***.
- ***Forrester*** decided that ***world population*** is a natural candidate to be chosen as an important state variable, as the world approaches its ***limits to growth***.
- Another important variable is ***pollution***, as too much pollution will clearly have tremendous effects on the ecological balance of the globe.

Selection of State Variables II

- A third good candidate is the ***amount of irrecoverable natural resources*** left. In 1971, it may have required vision to recognize that the exhaustion of fossil fuels will affect us in dramatic ways. Today, this is evident to us all.
- A fourth candidate is ***world capital investment***. More investment means more wealth, but also more pollution.
- A fifth and final candidate is the ***percentage of capital invested in the agricultural sector***. We evidently need food, and available capital can be invested in growing food.

Rate Variables and Laundry Lists I

- Each state variable was given a single inflow and a single outflow rate, except for the natural resources, which are only depleted.
- Let us look at the laundry list for the birth rate. ***Forrester*** postulated that the birth rate depends on:

Birth_rate = f (Population, Pollution, Food, Crowding, Material_Standard_of_Living)

- It may make sense to postulate that the birth rate grows proportionally with the population, thus:

Birth_rate = Population · f (Pollution, Food, Crowding, Material_Standard_of_Living)

Rate Variables and Laundry Lists II

- Since functions of four variables are difficult to identify, and at least, call for many observations, ***Forrester*** proposed a simplifying assumption: each ***multi-valued function*** can be represented as a ***product of single-valued functions***:

$$Birth\_rate = Population \cdot f_1\,(Pollution) \cdot f_2\,(Food) \cdot f_3\,(Crowding) \cdot f_4\,(Material\_Standard\_of\_Living)$$

- This assumption certainly is daring, but so is the entire enterprise.

Small-signal Behavior

- ***Forrester*** furthermore used a neat trick. He defined the values of all variables in the year 1970 as "normal," took these normal values out as a parameter, and formulated the functions as deviations from the norm, with values in the vicinity of 1.0:

$$\textit{Birth\_rate} = \textit{BRN} \cdot \textit{Population} \cdot f_1\,(\textit{Pollution}) \cdot f_2\,(\textit{Food}) \cdot f_3\,(\textit{Crowding}) \cdot f_4\,(\textit{Material\_Standard\_of\_Living})$$

- He proceeded in similar ways with all laundry lists of all rate variables.

Statistical Year Books I

- He then used ***statistical year books*** to propose sensible functional relationships for these factors.
- For example, it is known that the birth rate in third world nations with a low living standard is higher than in more developed countries.
- Thus, we could postulate a table, such as:

MSL	*BR*
0.0	*1.2*
1.0	*1.0*
2.0	*0.85*
3.0	*0.75*
4.0	*0.7*
5.0	*0.7*

Forrester's **world model contains 22 of these tables describing a wide variety of such statistical relationships among variables.**

Statistical Year Books II

	POLCM
CIR	*P_Generation*
0.0	0.05
1.0	1.00
2.0	3.00
3.0	5.40
4.0	7.40
5.0	8.00

	FPCI
CIRA	*Food_Ratio*
0.0	0.50
1.0	1.00
2.0	1.40
3.0	1.70
4.0	1.90
5.0	2.05
6.0	2.20

	BRCM	DRCM	FCM	QLC
Crowd_Rat	*Birth_Rate*	*Death_Rate*	*Food_Ratio*	*Qual_Life*
0.0	1.05	0.9	2.4	2.00
0.5				1.30
1.0	1.00	1.0	1.0	1.00
1.5				0.75
2.0	0.90	1.2	0.6	0.55
2.5				0.45
3.0	0.70	1.5	0.4	0.38
3.5				0.30
4.0	0.60	1.9	0.3	0.25
4.5				0.22
5.0	0.55	3.0	0.2	0.20

	BRFM	DRFM	CFIFR	QLF
Food_Ratio	*Birth_Rate*	*Death_Rate*	*CIAFG*	*Qual_Life*
0.00	0.0	30.0	1.00	0.0
0.25		3.0		
0.50		2.0	0.60	
0.75		1.4		
1.00	1.0	1.0	0.30	1.0
1.25		0.7		
1.50		0.6	0.15	
1.75		0.5		
2.00	1.6	0.5	0.10	1.8
3.00	1.9			2.4
4.00	2.0			2.7

	BRMM	CIM	DRMM	NRMM	QLM
MSL	*Birth_Rat*	*CI_Gen*	*Death_Rat*	*Depletion*	*Qual_Lif*
0.0	1.20	0.1	3.00	0.00	0.2
0.5			1.80		
1.0	1.00	1.0	1.00	1.00	1.0
1.5			0.80		
2.0	0.85	1.8	0.70	1.80	1.7
2.5			0.60		
3.0	0.75	2.4	0.53	2.40	2.3
3.5			0.50		
4.0	0.70	2.8	0.50	2.90	2.7
4.5			0.50		
5.0	0.70	3.0	0.50	3.30	2.9
6.0				3.60	
7.0				3.80	
8.0				3.90	
9.0				3.95	
10.0				4.00	

Statistical Year Books III

	NREM
NRFR	*ECIR*
0.00	0.00
0.25	0.15
0.50	0.50
0.75	0.85
1.00	1.00

	BRPM	DRPM	FPM	Polat	QLP
Poll_Rat	*Birth_Rat*	*Death_Rat*	*Food_Rat*	*P_Absorp*	*Qual_Lif*
0.0	1.02	0.92	1.02	0.6	1.04
10.0	0.90	1.30	0.90	2.5	0.85
20.0	0.70	2.00	0.65	5.0	0.60
30.0	0.40	3.20	0.35	8.0	0.30
40.0	0.25	4.80	0.20	11.5	0.15
50.0	0.15	6.80	0.10	15.5	0.05
60.0	0.10	9.20	0.05	20.0	0.02

	CIQR
QLMF	*CIAFG*
0.0	0.7
0.5	0.8
1.0	1.0
1.5	1.5
2.0	2.0

In each table, the left-most column lists the independent variable, whereas each of the other columns denotes one of the tabular look-up functions.

The top row lists the names of the functions. Underneath is the name of the variable that is being influenced by that table.

***Example*: BRPM lists the variability of the birth rate as a function of the pollution ratio.**

Rate Equations

- Using these table look-up functions, the ***rate equations*** can be formulated as follows:

$$Birth\_Rate = Population \cdot BRN \cdot BRCM \cdot BRFM \cdot BRMM \cdot BRPM$$

$$CIAFD = \frac{CIAF}{CIAFT}$$

$$CIAFG = \frac{CFIFR \cdot CIQR}{CIAFT}$$

$$CI\_Discard = CIDN \cdot Capital\_Investment$$

$$CI\_Generation = CIGN \cdot CIM \cdot Population$$

$$Death\_Rate = Population \cdot DRN \cdot DRCM \cdot DRFM \cdot DRMM \cdot DRPM$$

$$Depletion = Population \cdot NRUN \cdot NRMM$$

$$P\_Absorption = \frac{Pollution}{POLAT}$$

$$P\_Generation = Population \cdot POLN \cdot POLCM$$

Auxiliary Variables

- The following ***auxiliary variables*** are also being used:

$$CIR = \frac{Capital\_Investment}{Population}$$

$$CIRA = CIR \cdot \frac{CIAF}{CIAFN}$$

$$Crowding\_Ratio = \frac{Population}{Land\_Area \cdot Pop\_dens\_norm}$$

$$ECIR = NREM \cdot CIR \cdot \frac{1.0 - CIAF}{1.0 - CIAFN}$$

$$Food\_Ratio = FPCI \cdot FCM \cdot FPM \cdot \frac{FC}{FN}$$

$$MSL = \frac{ECIR}{ECIRN}$$

$$NRFR = \frac{Natural\_Resources}{NRI}$$

$$Pollution\_Ratio = \frac{Pollution}{POLS}$$

$$QLMF = \frac{QLM}{QLF}$$

$$Quality\_of\_Life = QLS \cdot QLC \cdot QLF \cdot QLM \cdot QLP$$

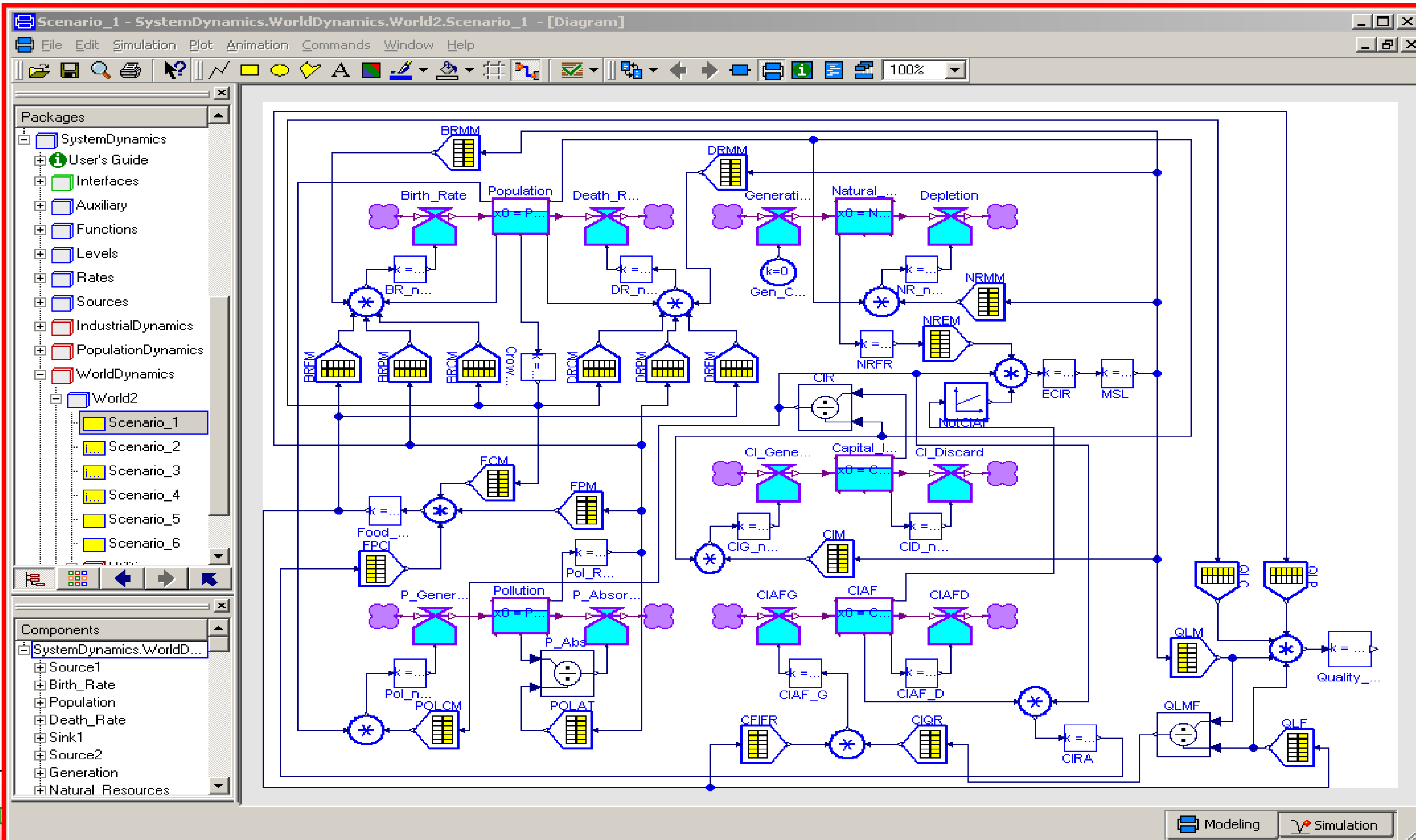
Parameters and Initial Conditions

$$BRN = 0.04 \quad (normal\ birth\ rate)$$
$$CIAFN = 0.3 \quad (CIAF\ normalization)$$
$$CIAFT = 15.0 \quad (CIAF\ time\ constant)$$
$$CIDN = 0.025 \quad (normal\ capital\ discard)$$
$$CIGN = 0.05 \quad (normal\ capital\ generation)$$
$$DRN = 0.028 \quad (normal\ death\ rate)$$
$$ECIRN = 1.0 \quad (capital\ normalization)$$
$$FC = 1.0 \quad (food\ coefficient)$$
$$FN = 1.0 \quad (food\ normalization)$$
$$Land\_Area = 1.35 \cdot 10^8 \quad (area\ of\ arable\ land)$$
$$NRI = 9.0 \cdot 10^{11} \quad (initial\ natural\ resources)$$
$$NRUN = 1.0 \quad (normal\ resource\ utilization)$$
$$POLN = 1.0 \quad (normal\ pollution)$$
$$POLS = 3.5999 \cdot 10^9 \quad (standard\ pollution)$$
$$Pop\_dens\_norm = 26.5 \quad (normal\ population\ density)$$
$$QLS = 1.0 \quad (standard\ quality\ of\ life)$$

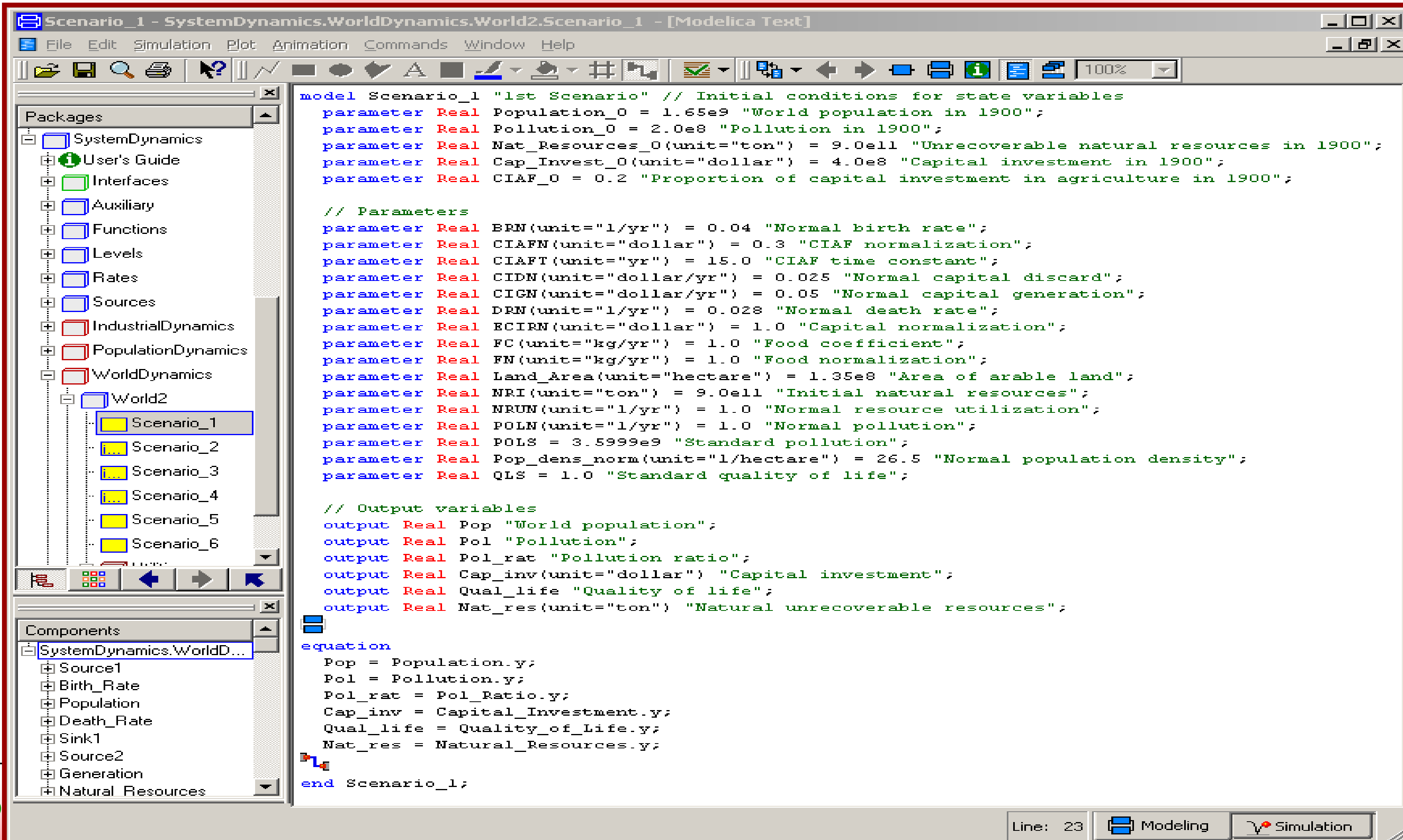
- The following ***parameters*** and ***initial conditions*** are being used:

$$Population = 1.65 \cdot 10^9$$
$$Pollution = 2.0 \cdot 10^8$$
$$Natural\_Resources = 9.0 \cdot 10^{11}$$
$$Capital\_Investment = 4.0 \cdot 10^8$$
$$CIAF = 0.2$$

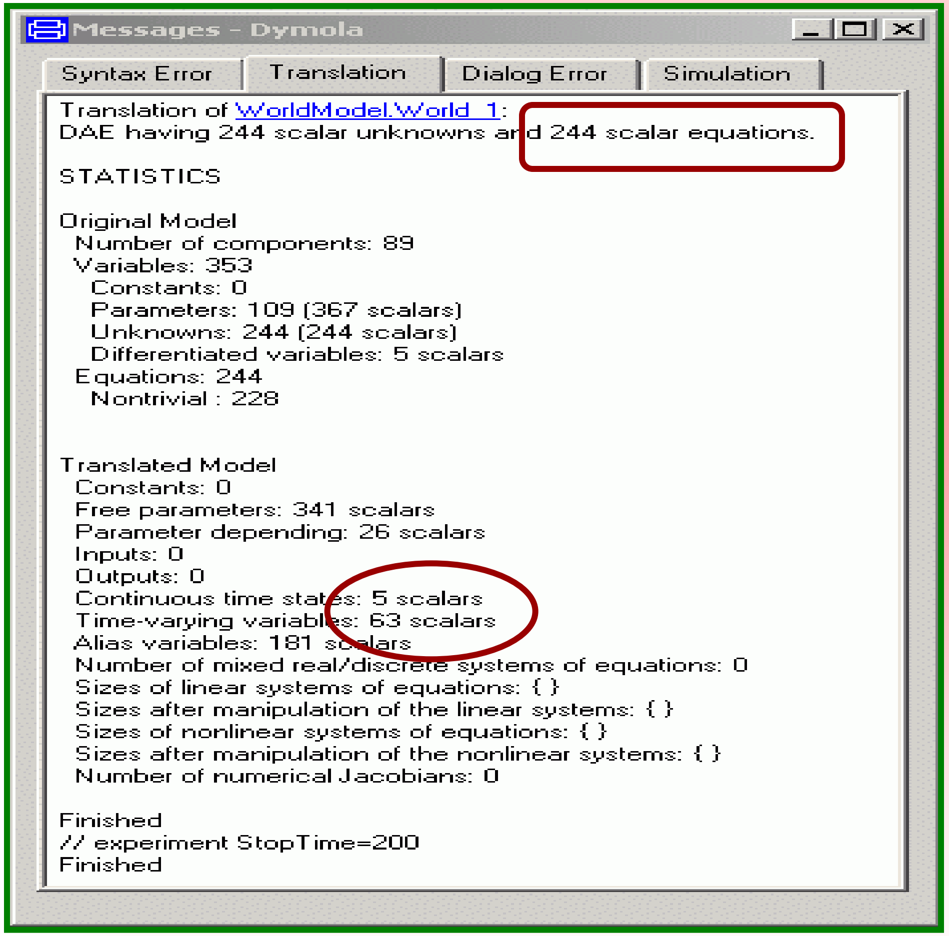
Overall World Model



Equation Window



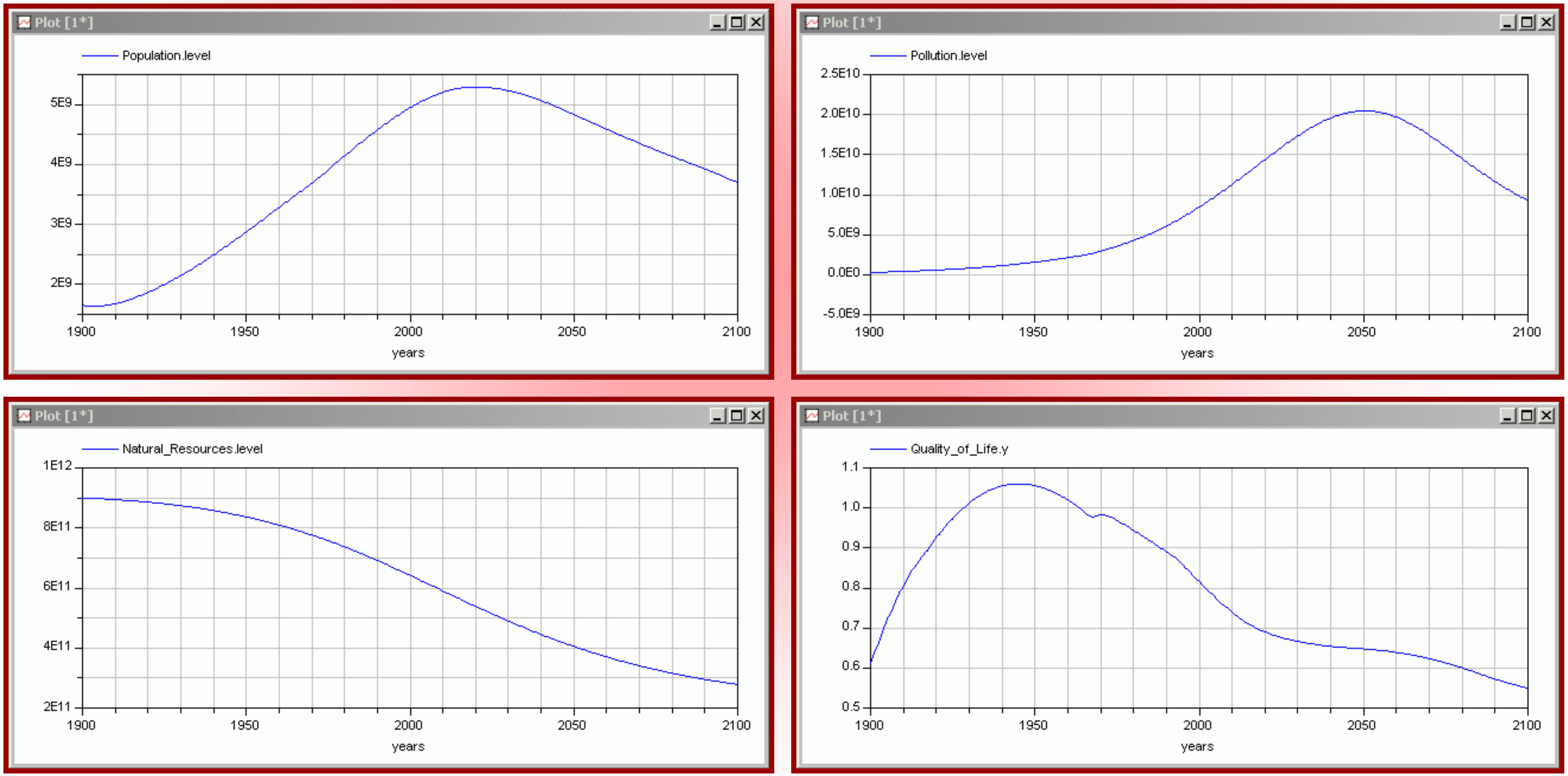
Compilation



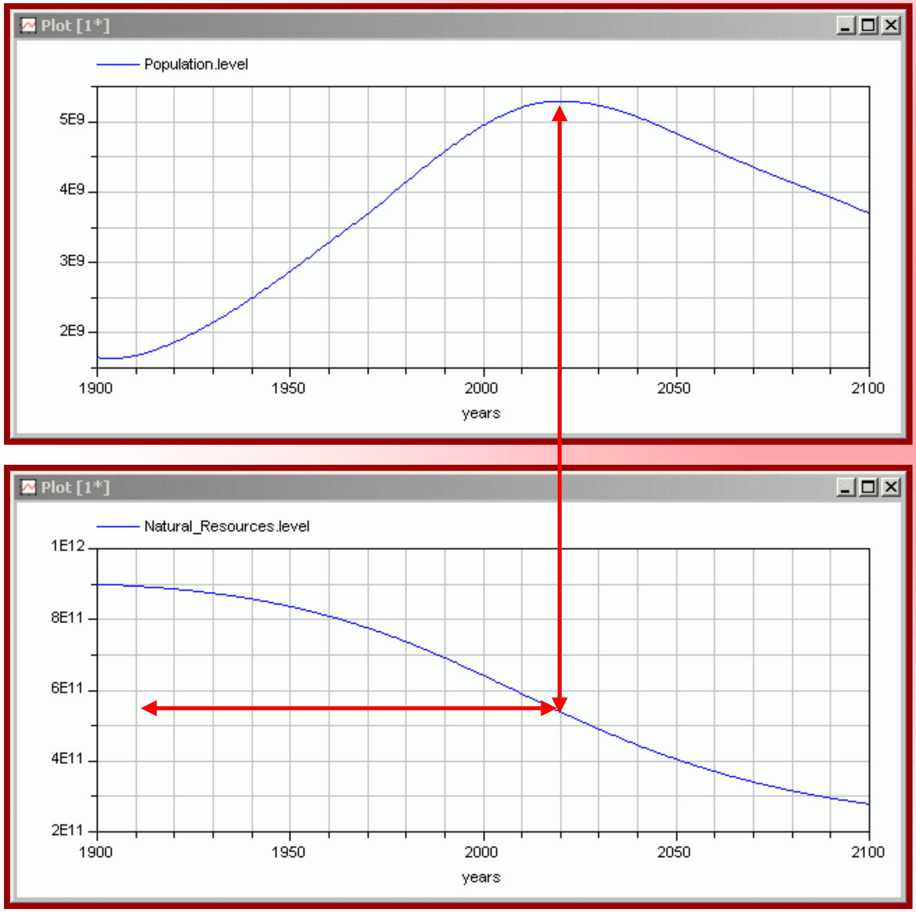
The diagram window shows a lot of structure for only *68 remaining equations*!

$\Rightarrow$ ***System dynamics*** **is a low-level modeling technique. Not very much is accomplished by the graphs. It may be almost as easy to work with the equations directly, instead of bothering with the graphical formalism.**

Simulation Results I



Simulation Results II



The model shows nicely the ***limits to growth***. The population peaks at about the year 2020 with a little over 5 billion people.

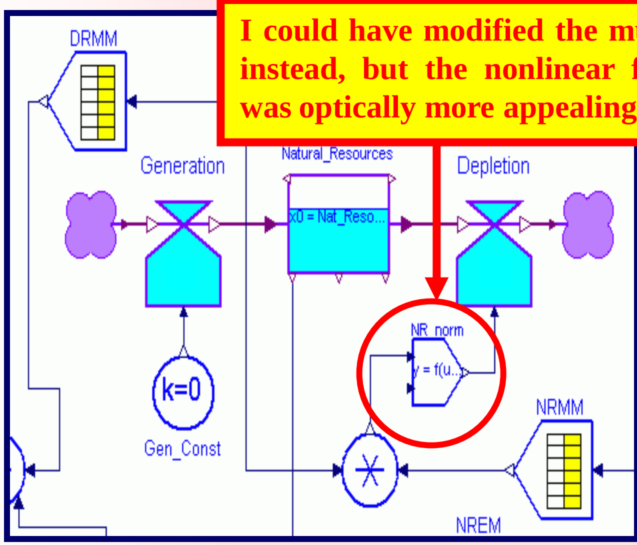
It turns out that, as the *natural resources* shrink to a level below approximately *5·10¹¹*, this generates a strong damping effect on the population.

1st Modification

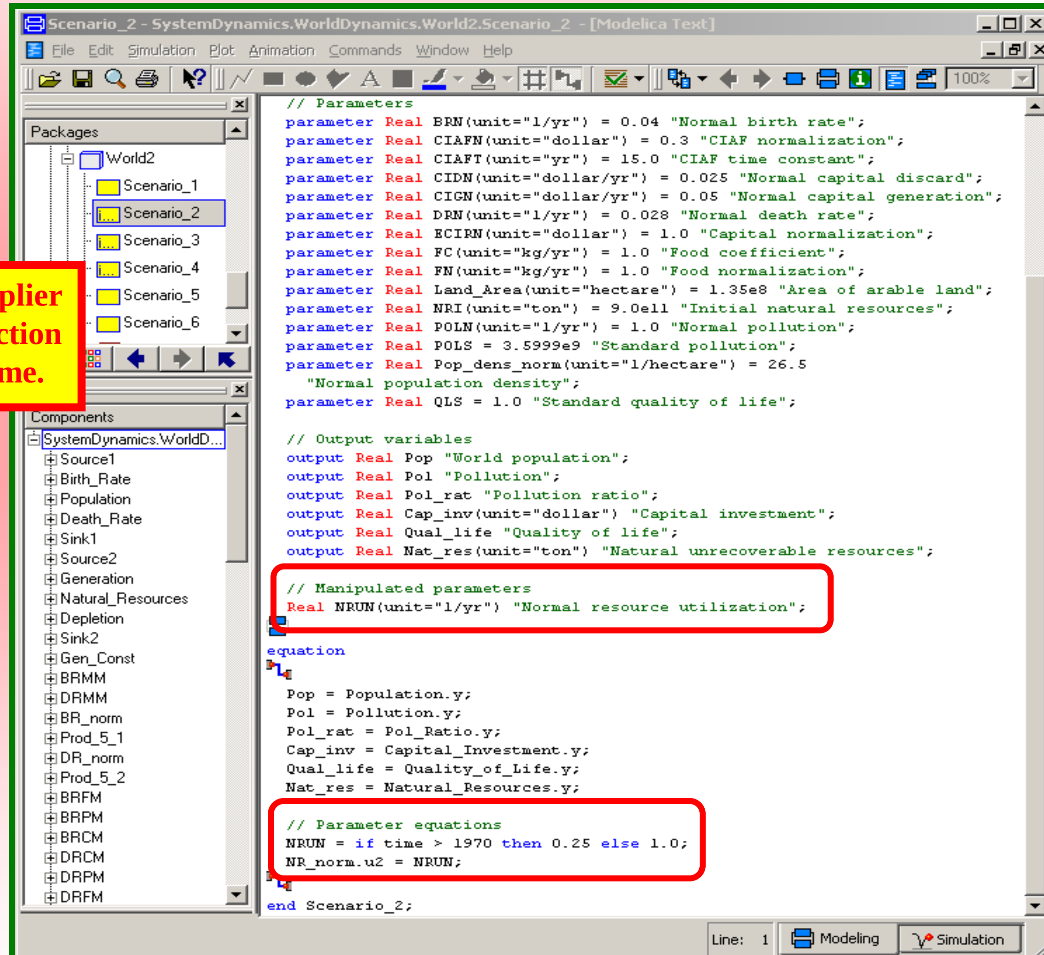
- ***Forrester*** thus proposed to ***reduce the usage of the natural resources by a factor of 4***, starting with the year 1970.
- This may be just as well. The effect of this modification is approximately the same as saying that more resources are available than anticipated. This is indeed true.
- Now, the resource exhaustion won't be effective as a damping factor any longer.

Program Modification I

- As we are now modifying a parameter, ***NRUN***, this former ***parameter*** had now to become a ***variable***.

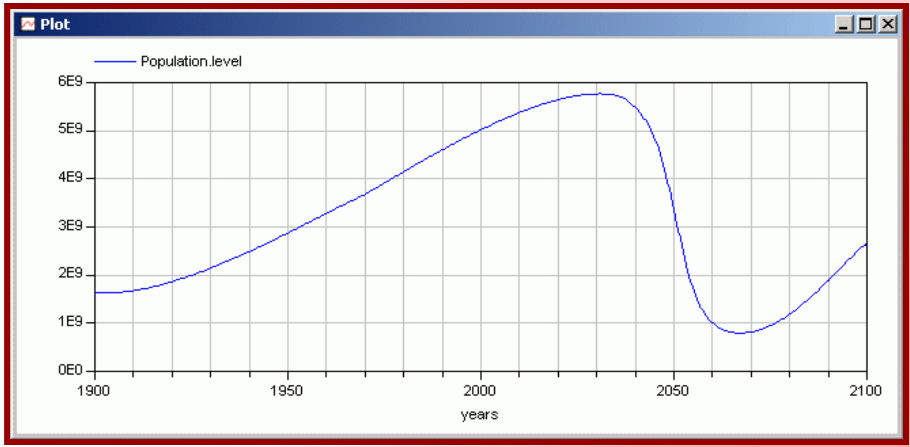


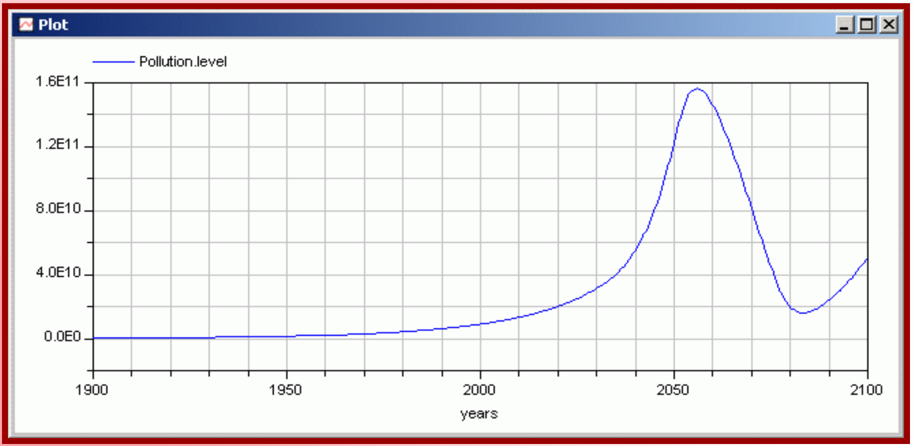
I could have modified the multiplier instead, but the nonlinear function was optically more appealing to me.

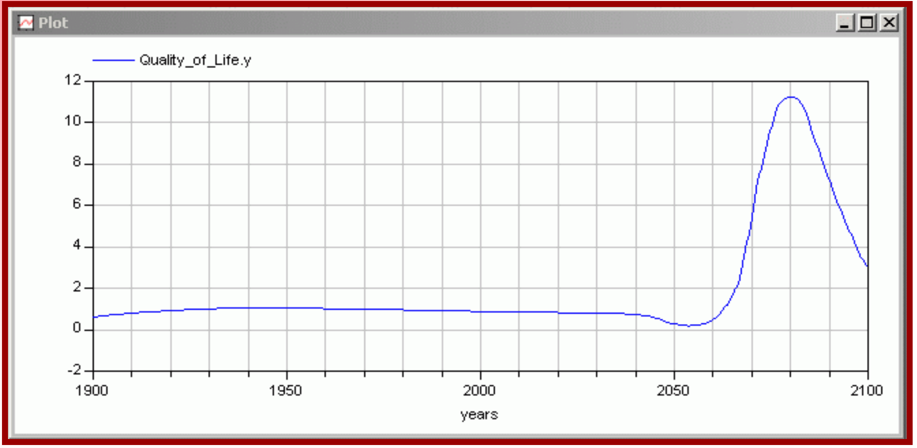


(I had to extend a few of the function domains to prevent the ***assert clauses*** in the ***Piecewise*** function from killing the simulation.)

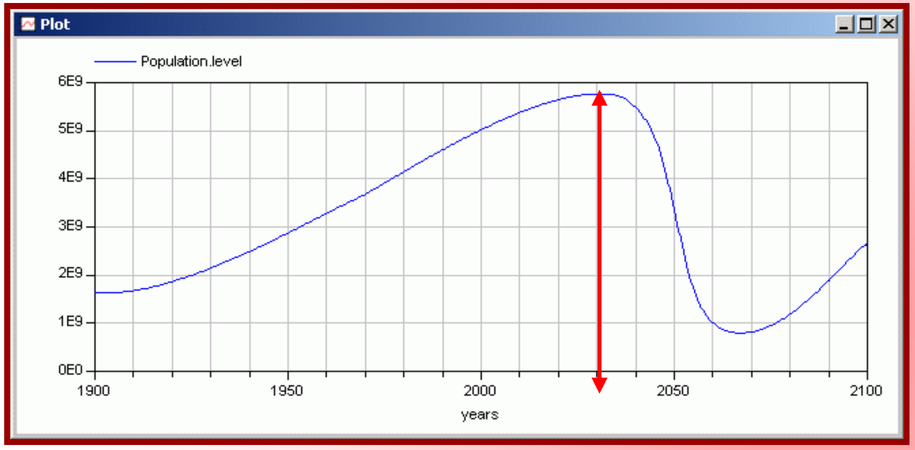
Simulation Results III

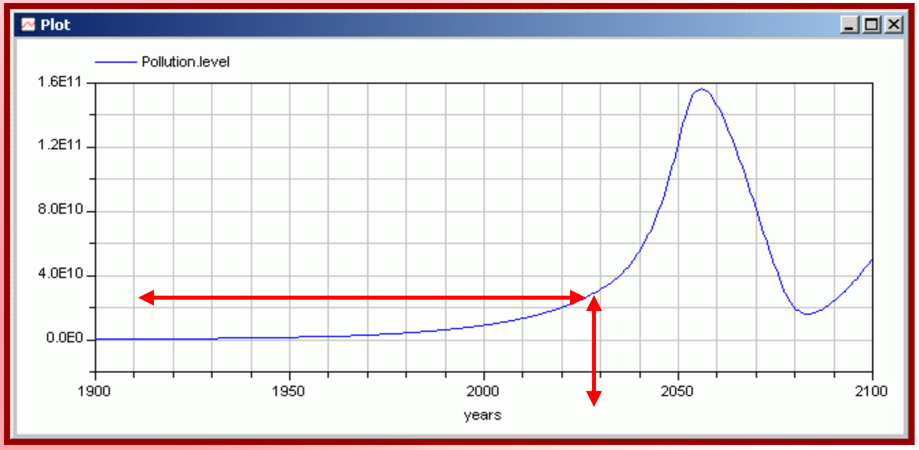






Simulation Results IV





This time around, the population peaks around the year 2035 at a level of approximately 5.8 billion people. Thereafter, the population declines rapidly in a ***massive die-off***. The natural resources are not depleted until after the year 2100.

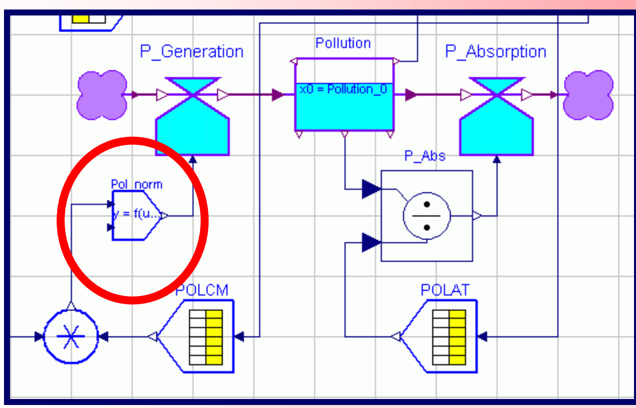
This time around, it is the pollution that reaches a critical level.

2nd Modification

- Forrester thus proposed to additionally ***reduce the production of pollution by a factor of 4***, starting with the year 1970.
- This may not be as reasonable an assumption. Yet at least in the industrialized nations, a lot has been done in recent years to clean up the lakes and reduce air pollution.
- Now, the pollution factor won't be effective as a population killer any longer.

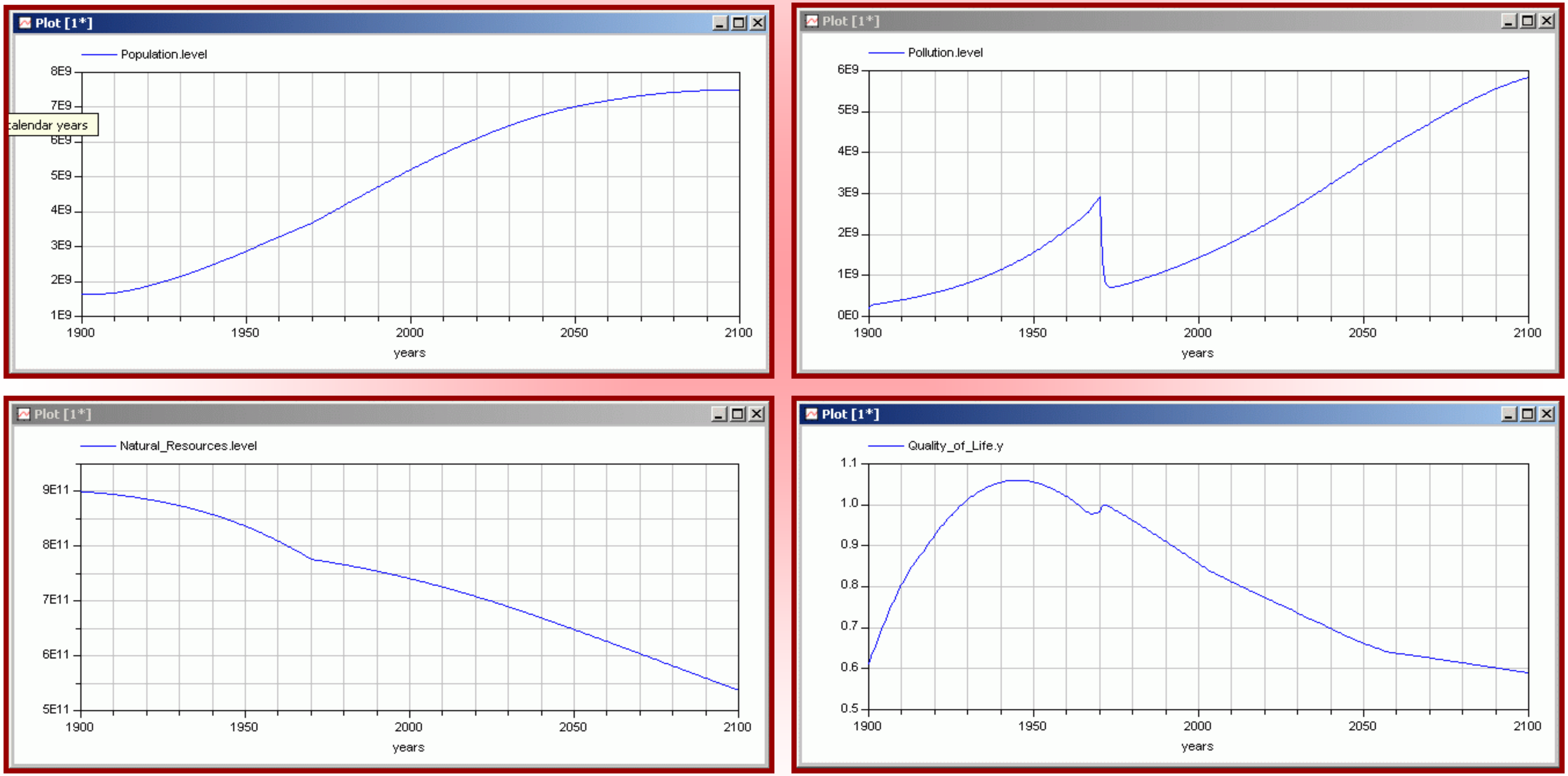
Program Modification II

- As we are now modifying another parameter, ***POLN***, this former ***parameter*** must now also become a ***variable***.



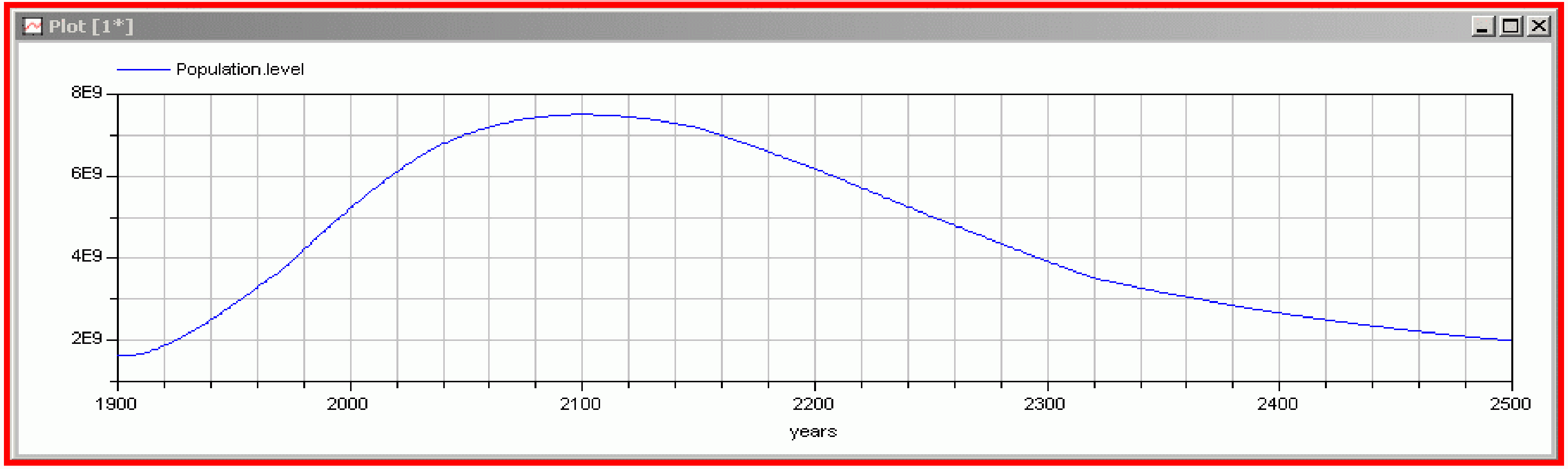

```
  // Manipulated parameters
  Real NRUN "Normal resource utilization";
  Real POLN "Normal pollution";

equation
  years = time + 1900;

  // Parameter equations
  NRUN = if years > 1970 then 0.25 else 1.0;
  NR_norm.u2 = NRUN;
  POLN = if years > 1970 then 0.25 else 1.0;
  Pol_norm.u2 = POLN;

end World_3;
```

Simulation Results V



Discussion I

- This is where ***Forrester's*** book ends. He plotted the population curve on a double page, stipulating (though he never wrote so explicitly) that this is what we need to do to overcome the hump problem.
- Evidently, this conclusion is erroneous. If we look at the natural resources, we see that by 2100, they have again depleted to a level, where the population curb will set in.
- Let us simulate further:

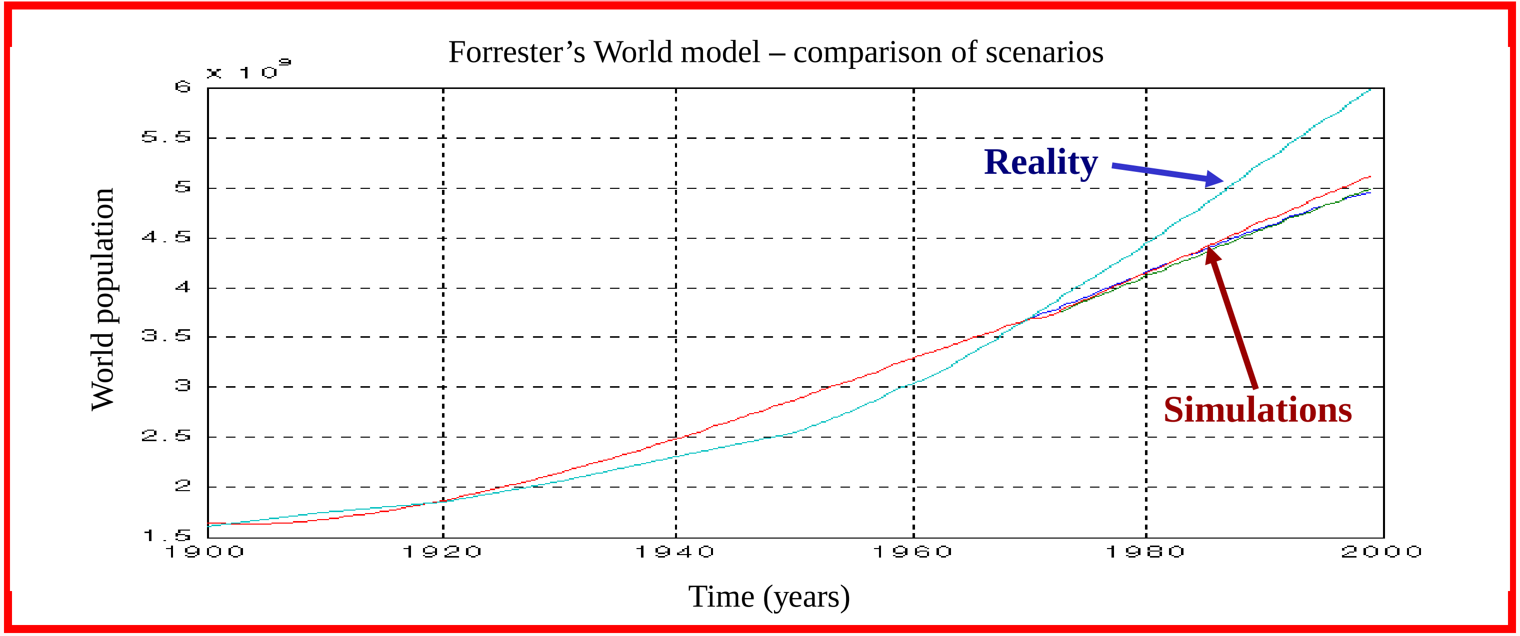


Discussion II

- The results are very similar to those of the original model, except that the population now had a chance to climb to almost 8 billion people before declining again, and that the hump takes place 80 years later.
- This by itself is not unreasonable: ***Forrester*** is saving the planet one day at a time, and his attention span is certainly longer than that of most politicians who aren't interested in saving the world beyond the next election date!

Hindsight is Always 20/20

- Since ***Forrester*** developed his world model, more than 40 years have passed.
- It thus makes sense to compare his predictions with the meanwhile observed reality.



Program Modification III

- The reality is far worse than ***Forrester's*** worst nightmare. The world population grows much faster than he had predicted.
- ***Forrester*** had not taken into account the amazing progress of medicine. People live longer than ever before [at least in most parts of the world – in Russia, life expectancy declined by 10 years after the end of the Soviet Union, and in Southern Africa, people die as young as ever before due to AIDS], and the infant mortality is at an all-time low.
- To accommodate for this progress, let us reduce the ***death rate*** in 1970 from ***0.028*** to ***0.02***.

Simulation Results VI

- The fit is now reasonably good. Let us check what this modification does to the longer-term simulation.

Discussion III

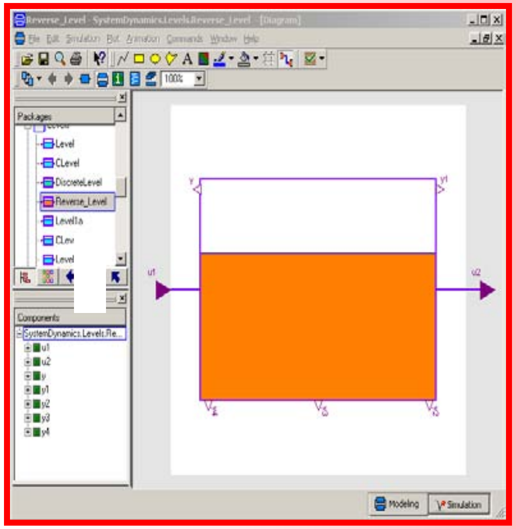
- Not much has changed in the longer run. The population rises now to approximately 8 billion people, before decaying again down to the same 2 billion people in steady-state that all of the other simulations have shown.

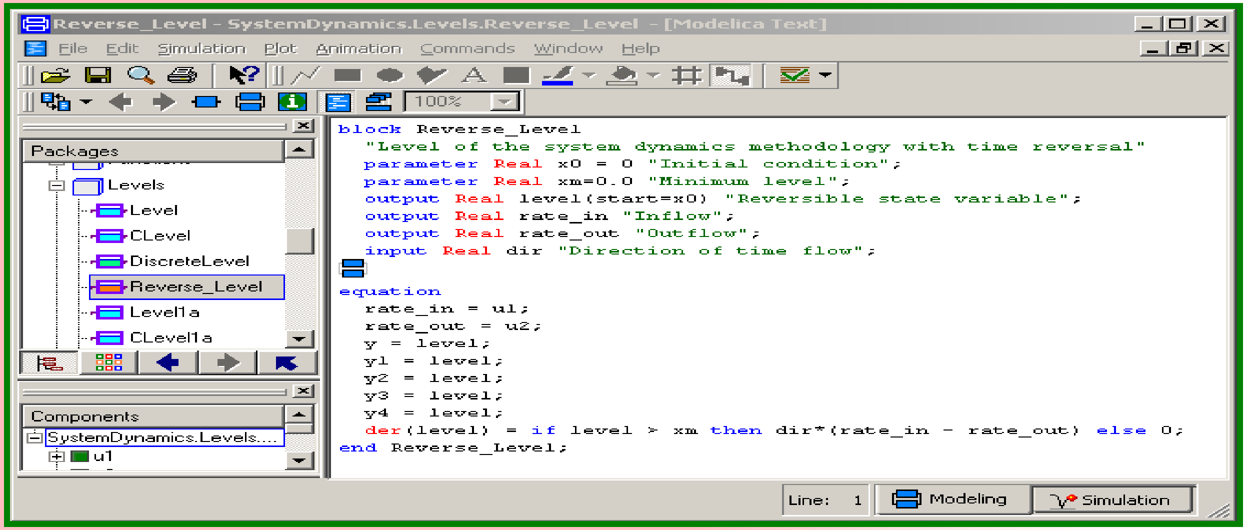
Model Validation

- Let us discuss, how we may be able to validate or disprove the model.
- One neat trick is to ***simulate backward in time*** beyond 1900. Since we know the past, we may be able to conclude something about the validity of the model.
- Simulation backward through time can be accomplished by placing a minus sign in front of every state equation.
- If all time derivatives have reversed signs, the same trajectories are generated, but the flow of time is now reversed.

A New Level Block

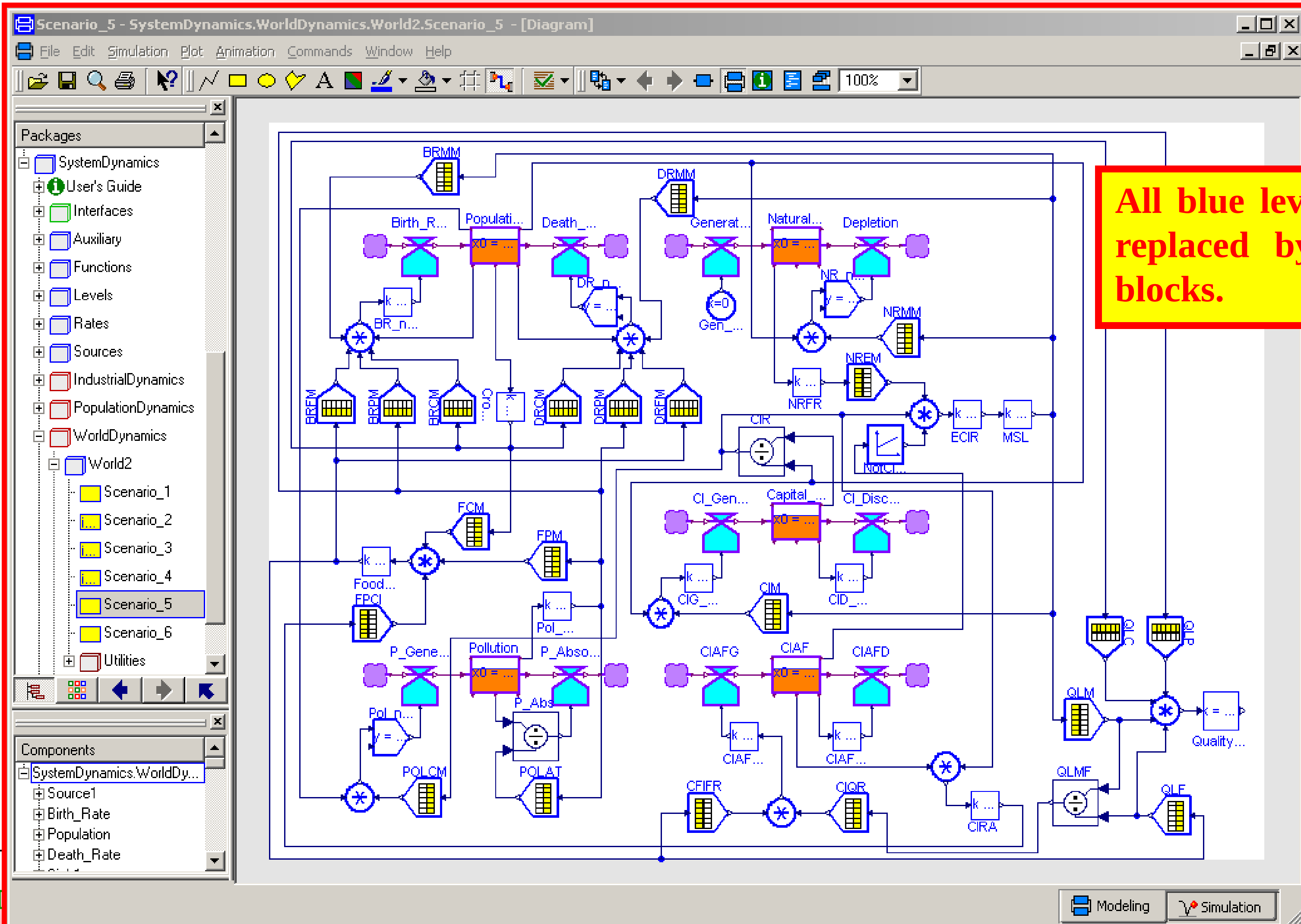
- To this end, a new ***reverse level block*** was introduced.





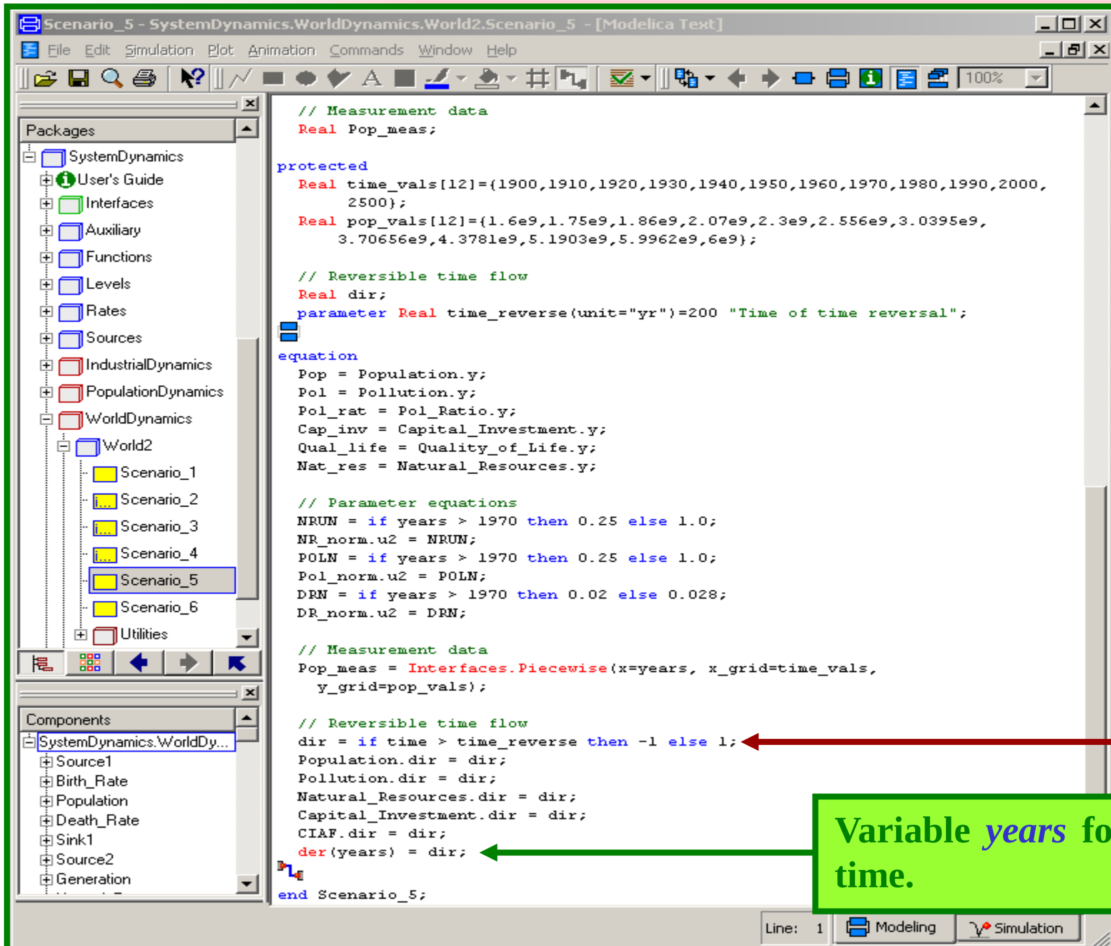
- The brown levels contain a variable ***dir***. When ***dir* = +1**, the direction of time flow is positive, when ***dir* = –1**, it is reversed.
- I furthermore introduced a minimum level ***xm***, which ensures that e.g. none of the state variables of the world model can ever become negative.

Program Modification IV



All blue level blocks were replaced by brown level blocks.

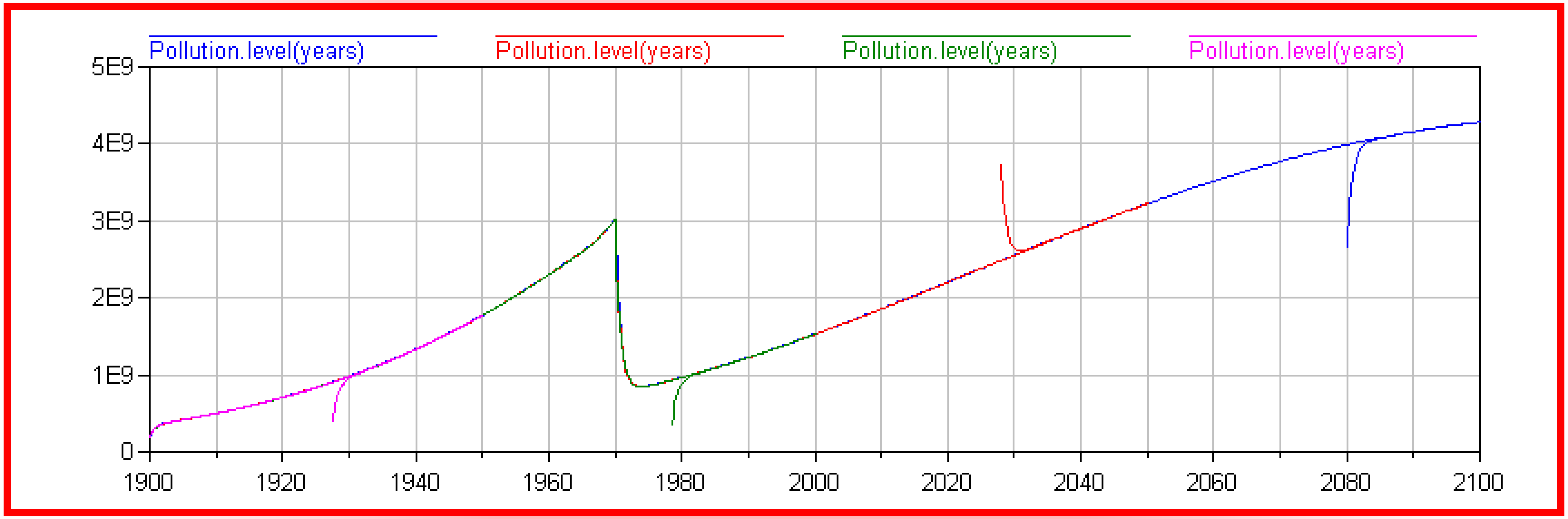
Program Modification IV - 2



Until *time* = *time_reverse*, the simulation proceeds forward in time, then the flow of time is reversed.

Variable *years* follows the flow of time.

Simulation Results VII



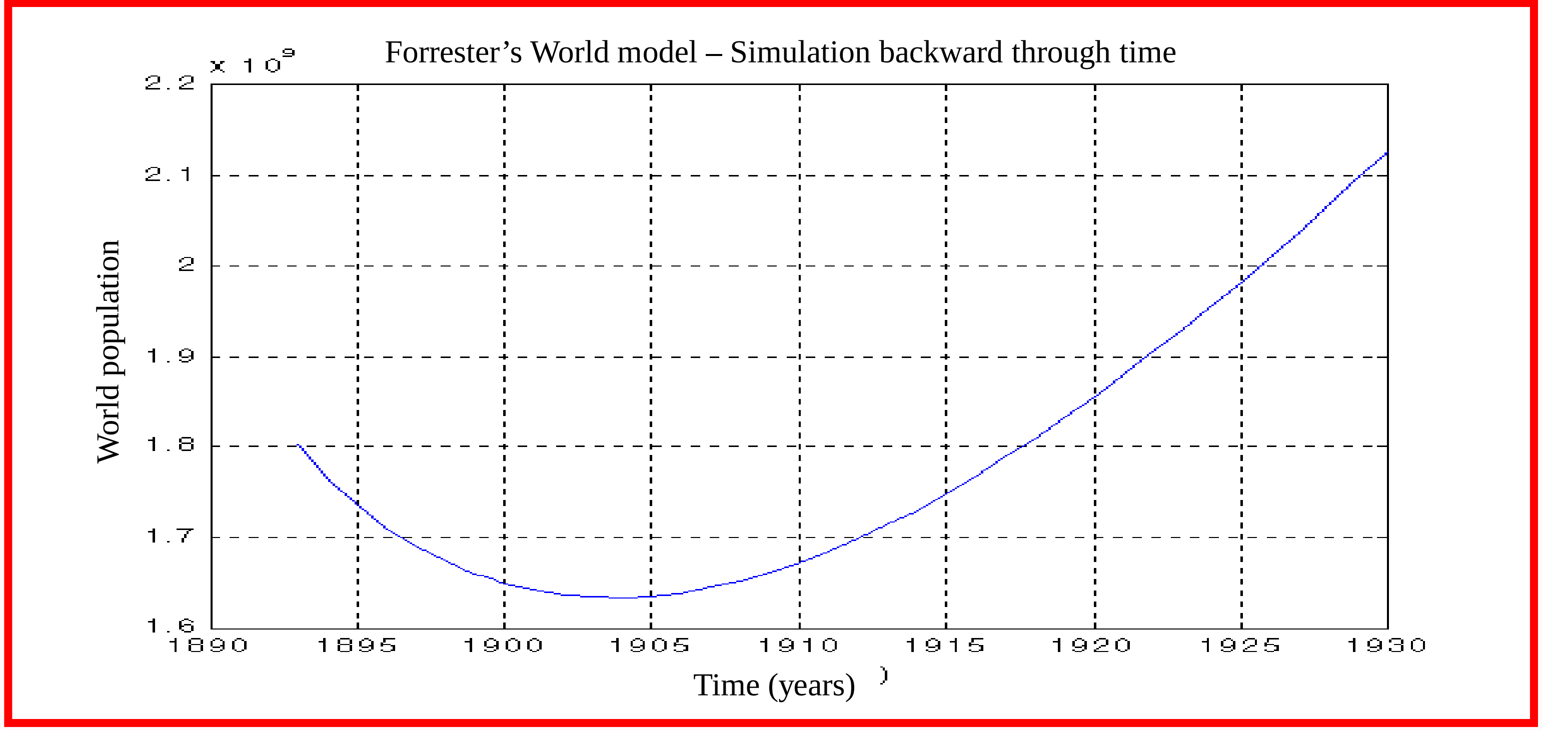
- I first simulated forward through time during 200 years, then reversed the flow. The reversal worked well for about 16 years, after which the trajectories separate.
- I superposed another simulation, where I simulated forward during 150 years, then backward again. The trajectories separate after 18 years.

Discussion IV

- The simulation is ***numerically unstable*** in the backward direction.
- The culprit is the ***pollution absorption equation***. The tiniest deviation from the correct trajectory leads to an exponentially increasing error.
- Special ***stabilization techniques*** are needed to simulate backward through time. A discussion of those is beyond the scope of this class. One possible algorithm varies the initial pollution value at each integration step such that the sensitivity of the solution to the initial value is minimized.

Simulation Results VIII

- The results shown below are for a simulation forward in time over 30 years, then backward in time over 37 years.



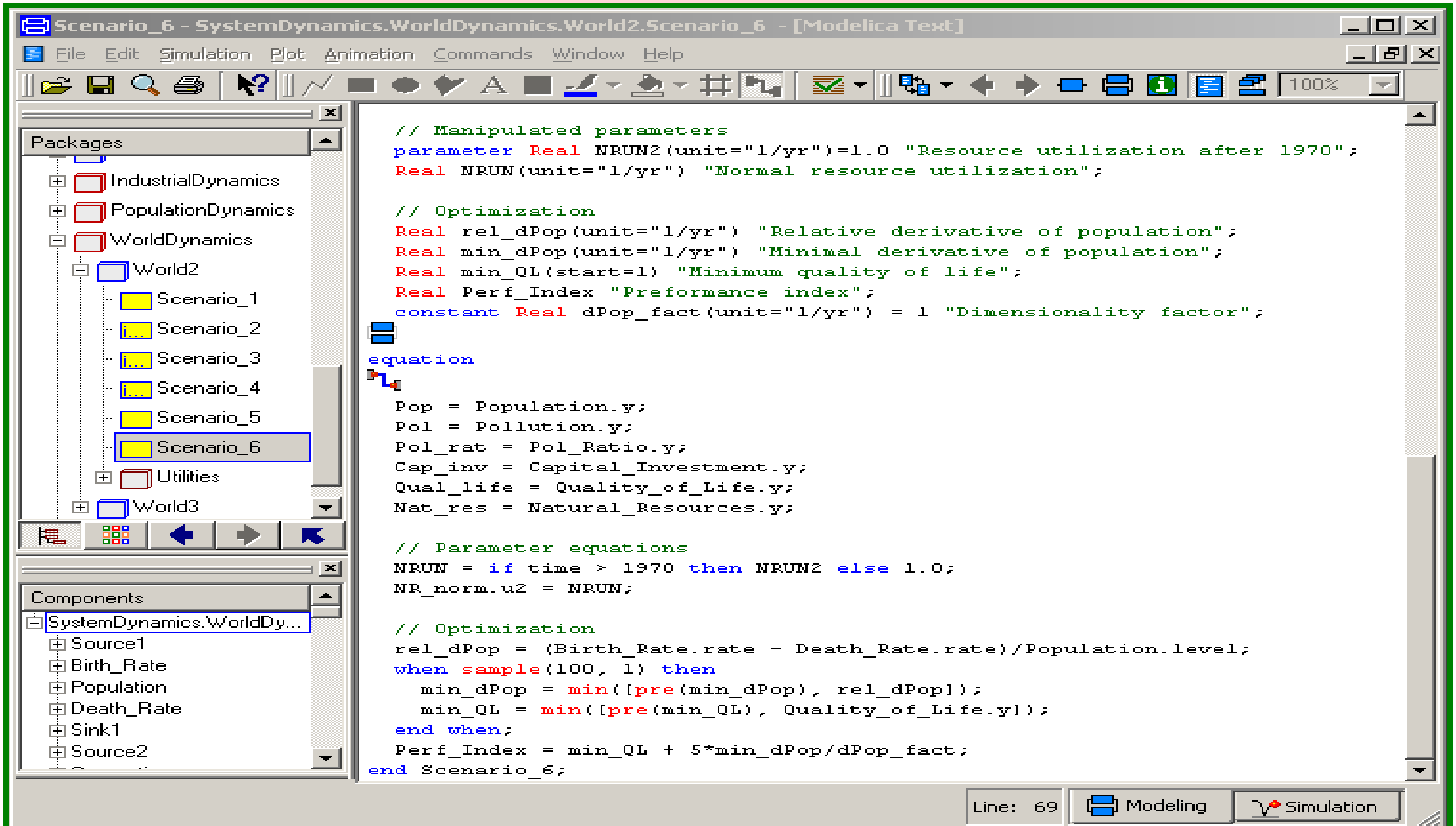
Discussion V

- The simulation suggests that the world population was declining before 1900, reaching a minimum around 1904.
- We know that this is totally incorrect. So, how can we hope to simulate correctly until the year 2500?
- Evidently, we cannot! We shall see, however, what valid conclusions can still be drawn from the model.

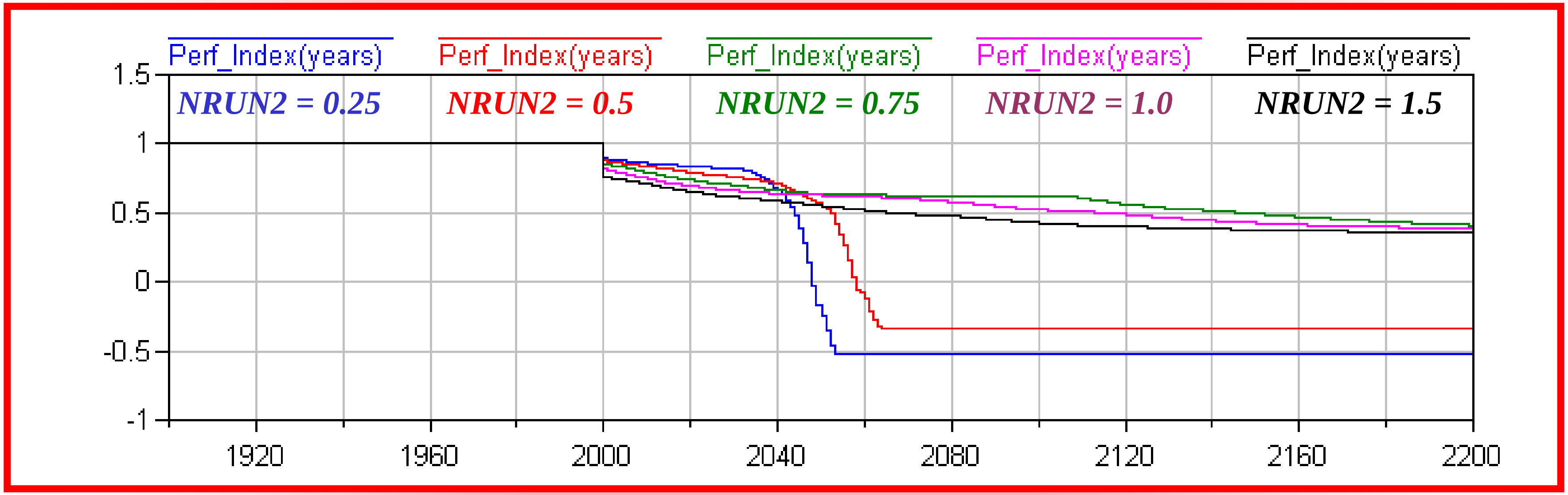
Optimization

- Let us now return to the model after the first modification.
- We want to ***optimize*** the ***consumption of natural resources*** after the year 1970.
- To this end, we shall need a ***performance index***. What is ***good***, is a ***high value of the minimal quality of life*** after the year 2000 (optimizing the past doesn't make much sense). What is ***bad***, is a ***die-off of the population***.
- Accordingly, we modify the program once more. This is all done in the ***equation window***.

Program Modification V



Simulation Results IX



- The first two simulations are plagued by ***massive die-off***. The others are fine.
- Yet, in the short run, those solutions that will give us bad performance (die-off) exhibit the best performance.

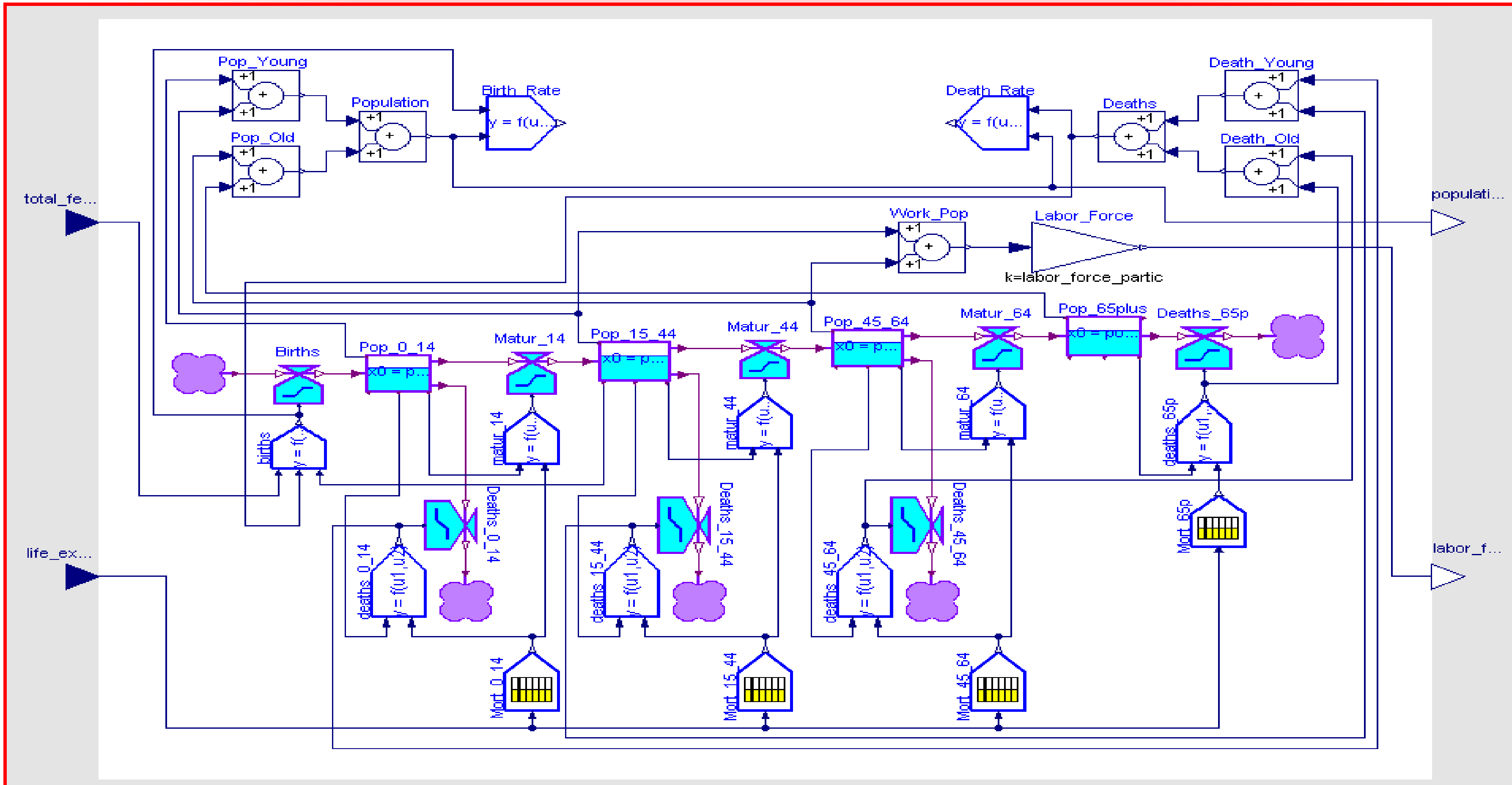
Discussion VI

- Politicians have a tendency to focus on short-term performance. Their "attention span" usually ends with the next election date.
- Consequently, they will most likely favor a solution that will lead to a ***massive die-off*** further down the line (***après moi le déluge!***).

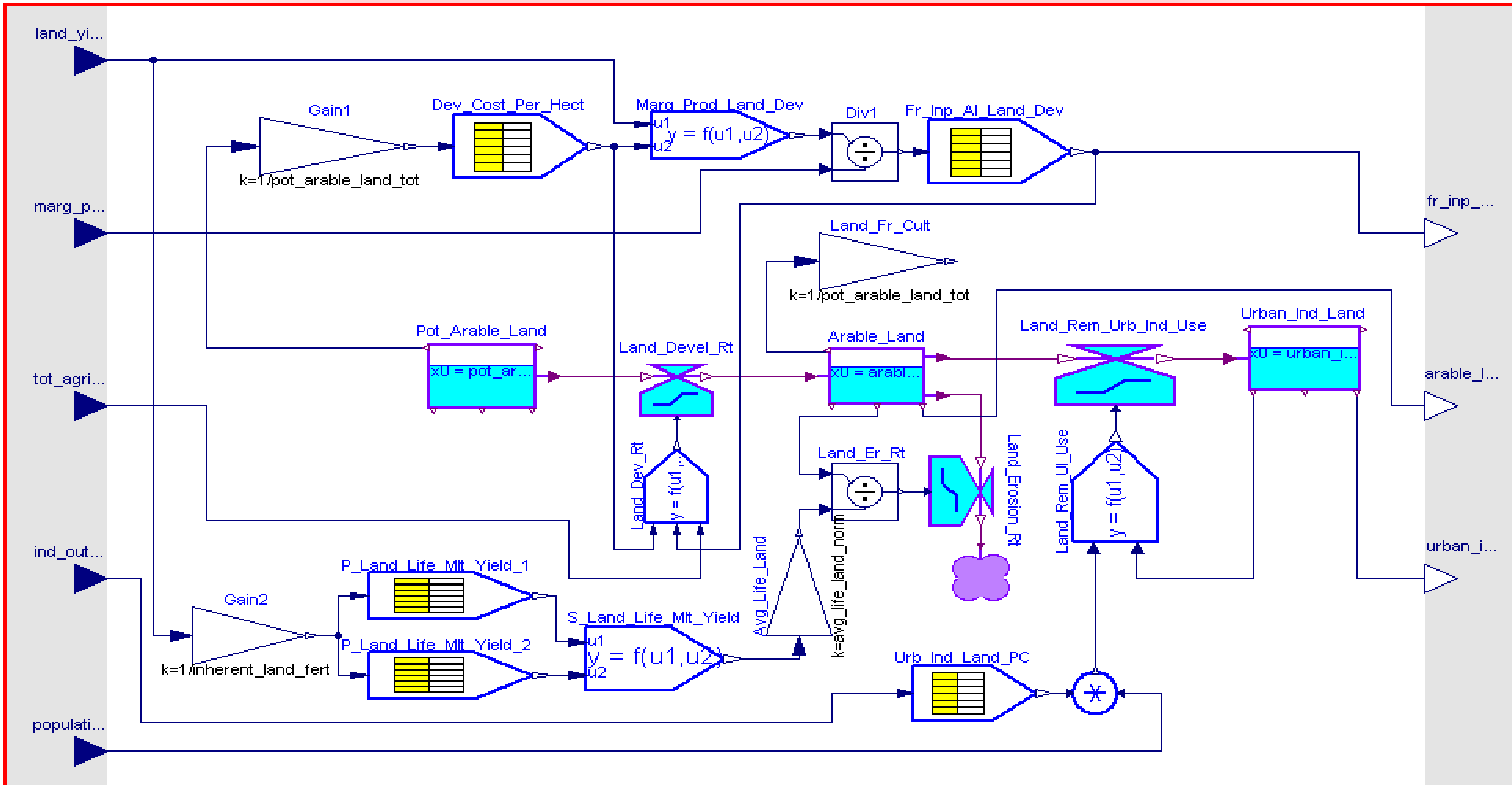
How Good Is The Model?

- We may ask ourselves, how good the model is that ***Forrester*** created. After all, the model contains lots of assumptions that may or may not be valid.
- One way to find out is to compare that model with another world model created by a different group of researchers (albeit from the same institution) using a different set of variables.
- The second model is called ***World3***. It was created by ***Dennis Meadows*** and his students. It is a considerably more complex (higher-order) model.
- The ***World3*** model is also contained in full in the ***SystemDynamics*** library.

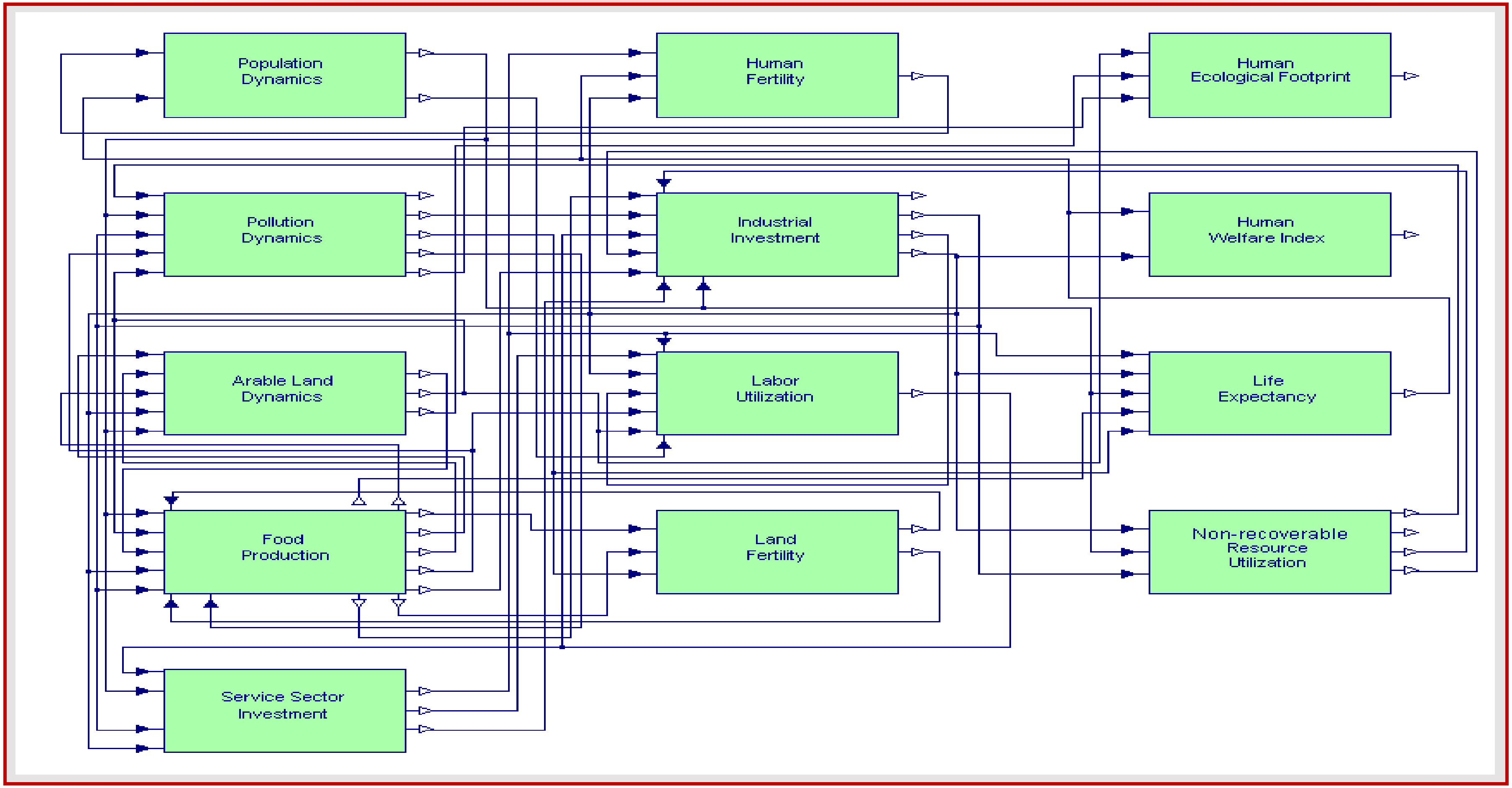
World3: Population Dynamics



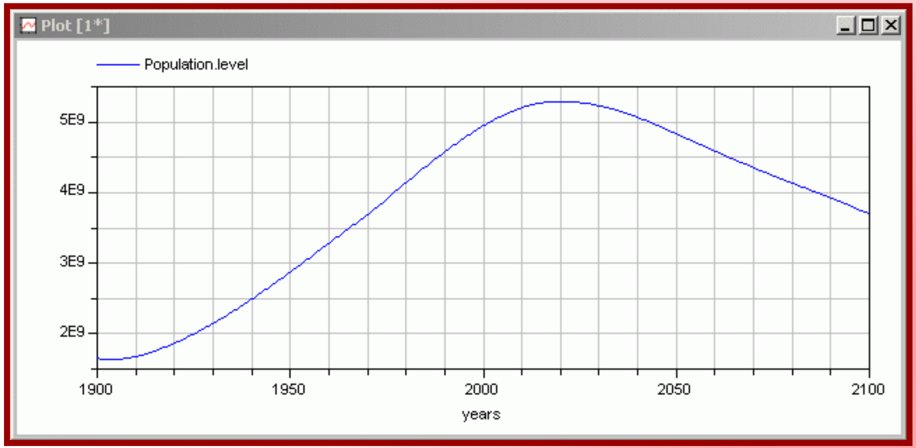
World3: Arable Land Dynamics



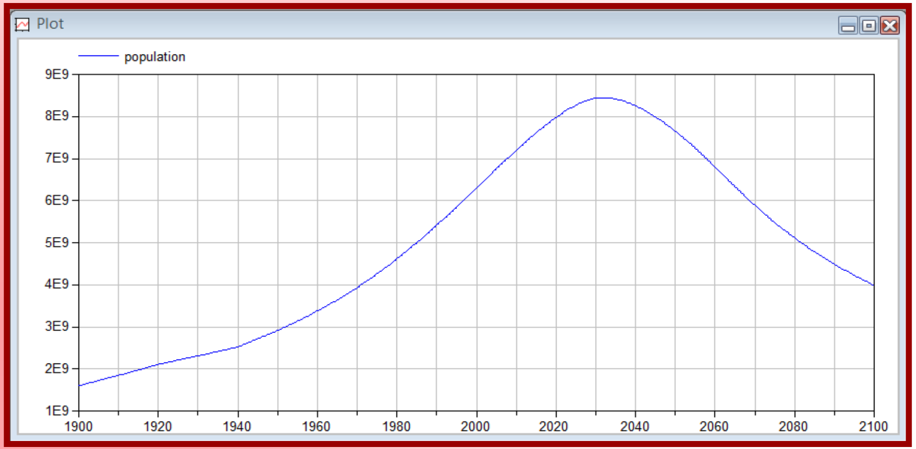
World3: Complete Model



World2 and World3: Base Scenario (BAU)



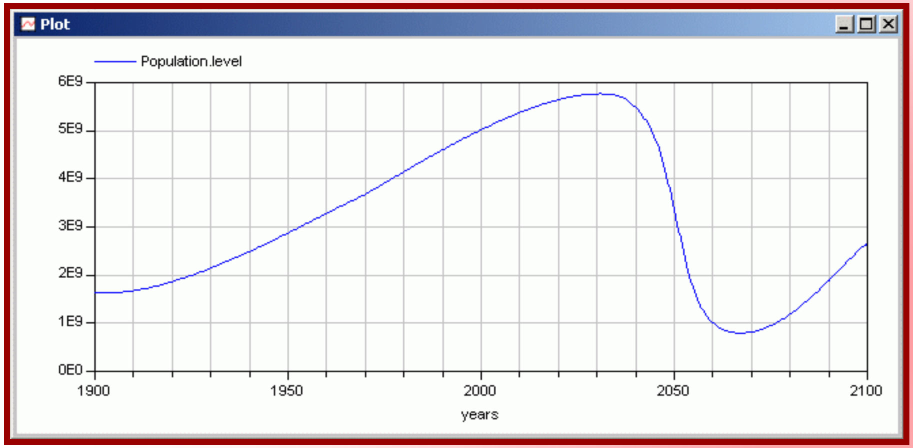
World2: Population



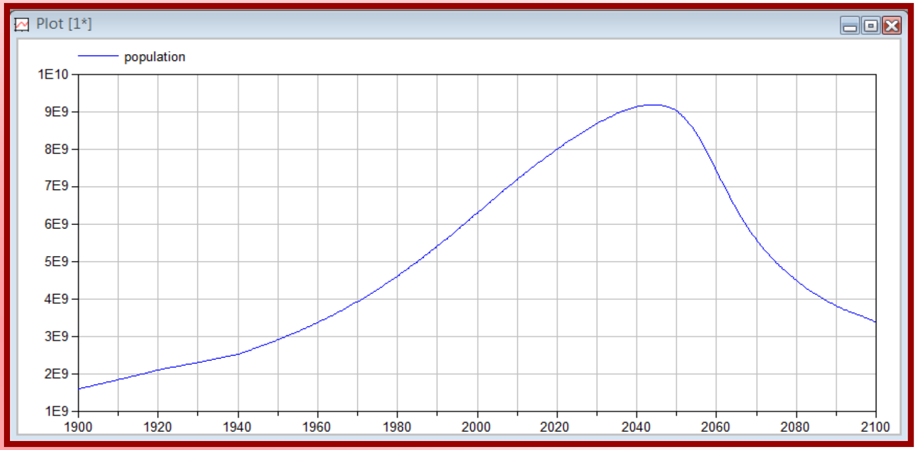
World3: Population

- The two models exhibit qualitatively the same behavior. The population peaks during the first half of the 21st century, and thereafter, it decreases again rapidly.

World2 and World3: More Energy Scenario



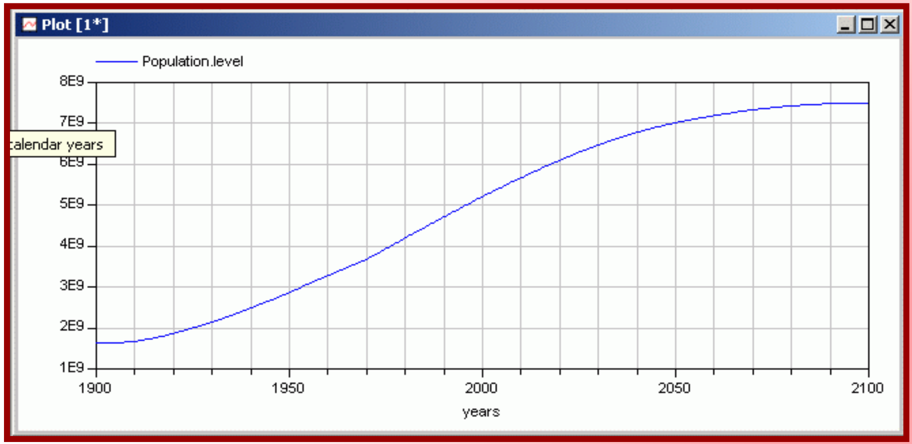
World2: Population



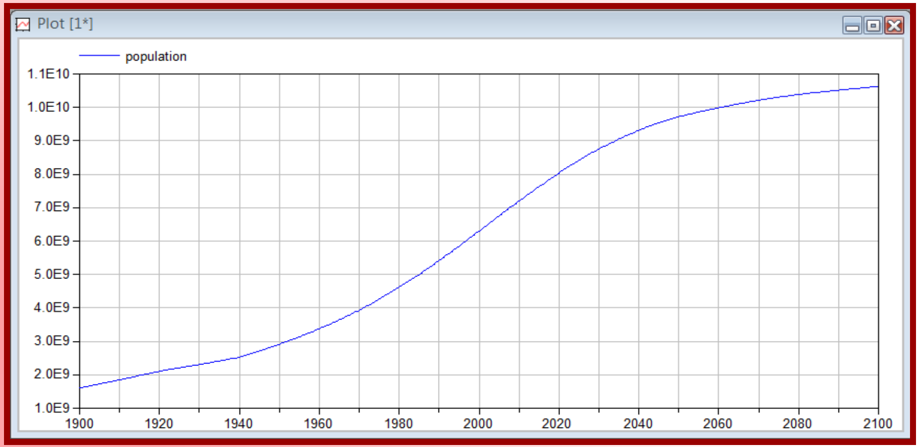
World3: Population

- The two models once again exhibit qualitatively the same behavior. The population peaks only a few years later, and the subsequent decay is more rapid.

World2 and World3: Improved Scenario



World2: Population



World3: Population

- The two models still exhibit qualitatively the same behavior. The population peak is delayed until the end of the century.

Conclusions I

- So, what can we conclude from these models?
- The answer is simple: We need to perform a ***sensitivity analysis*** to determine, which answers are least sensitive to both the overt and the hidden assumptions made in the models.
- All simulations show that the ***limits to growth*** are imminent. For the first time in recorded history, for the first time even since Adam and Eve were expelled from paradise [because the devil (the ***Great Innovator***, the who maximizes entropy) seduced them to becoming smart … and smartness comes at a price: ***intelligent beings*** are expected to assume ***responsibility*** for their actions], Earth is proceeding from a system with seemingly unlimited resources to one that is severely resource limited.

Conclusions II

- Hence we need to take the entire food and fresh water that Earth can produce, and divide these resources into the number of people. There is not one fixed equilibrium. We can either live in smaller numbers well, or in larger numbers with hunger.
- One would hope that, being ***intelligent***, mankind would opt for the former solution. Yet, there is little evidence to this effect, and much evidence to the contrary. It seems that our intelligence only helps us in a local context. In a global setting, we behave not much different from cultures of yeast … except that we are aware that this is what we are doing, whereas yeast is not.

Conclusions III

- Our ***fiat economy*** has made us believe that all problems can be solved by printing more money. Yet, money cannot be eaten. Ultimately, someone has to grow the food that we are eating.
- By burning fossil fuels, we are using resources that we have not produced. It is like spending money that we won in the lottery.
- Once the fossil fuels are gone, we will have to produce everything that we spend.
- A given number of people can only produce a fixed amount of goods.

Conclusions IV

- If Earth can carry well a certain number of people in steady state, and if this number is smaller than the current population, which may well be the case [***Forrester's*** model suggests roughly 2 billion people, but this number may not be entirely correct, though it won't be very far off], then it doesn't help to design mechanisms that will ensure that the population can grow further over a short period of time. This only means that it will have to come down again later, and may do so violently (***massive die-off***).
- Yet, our politicians will do everything in their power to keep the GNP growing for a few more years, which can only be accomplished with a larger population.

Conclusions V

- More people means ***more tax payers***. More people also means a ***younger population***, i.e., more people contributing to the ***social security funds***.
- Yet, more people also means a larger decline later. It also means an increase in the feedback gains, which implies a destabilization, i.e., an increased risk of ***massive die-off***.
- Will humanity be ***smart***, or will we be ***greedy***?
- We are most certainly living in interesting times!

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