UBA
Universidad de Buenos Aires

DEPARTAMENTO
DE COMPUTACION
Facultad de Ciencias Exactas y Naturales - UBA

Overview of the Modelica-based World2 and World3 models

Prof. Dr. Rodrigo Castro

rcastro@dc.uba.ar

MODELING OF SUSTAINABLE ECONOMIC SYSTEMS

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- This lecture borrows several pieces of content from presentations on global modeling and the Modelica-based library for System Dynamics kindly made available by Prof. Dr. François E. Cellier (emeritus), ETH Zurich

World2 (Forrester, 1971)

- In 1971, J.W. Forrester published World2, developed for the Club of Rome offering predictions about the future of our planet

- World2 is a simple 5th-order differential equation model
  - The book World Dynamics sold immediately several million copies translated into many languages
  - Forrester was strongly criticized by many colleagues, in particular economists

- World3 (Meadows et al, 1972) is a sophistication of World2
  - The underlying modeling philosophy and technique are exactly the same, relying on the ***System Dynamics*** methodology

The System Dynamics Recipe

- 1 - Start out by choosing the Levels to be included in the model
  - These must be quantities that can be accumulated
- 2 - For each Level, define its Rates as
  - one or several additive Inflows
  - one or several additive Outflows
- 3 - For each Rate, define a **Laundry List** comprised of the set of most influential Factors.
- 4 - For each Factor, define **Equations** that relate factors back to the Levels, the Rates, and the other Factors.
  - These Equations should be created by using as much physical insight as possible

The System Dynamics Recipe

Levels	Rates	
	Inflows	Outflows
Population	**Birth Rate**	**Death Rate**
Money	Income	Expenses
Frustration	Stress	Affection
Love	Affection	Frustration
Tumor Cells	Infection	Treatment
Inventory on Stock	Shipments	Sales
Knowledge	Learning	Forgetting

Laundry List: Birth Rate

Birth Rate ←

- Population
- Material Standard of Living
- Food Quality
- Food Quantity
- Education
- Contraceptives
- Religious Beliefs

Selection of Levels: State Variables

- Which variables should be used as state variables? How many of those are needed?
- In large complex systems there obviously is no good answer to these questions
  - No doubt, the entire world belongs to this category
- For World2, Forrester decided that world population is a natural candidate to be chosen as an important state variable
  - Encompasses the concern about a world approaching its limits to growth
- Another important variable is pollution
  - Too much pollution can clearly produce tremendous effects on the ecological balance of the globe

Selection of State Variables

- A third good candidate is the amount of irrecoverable natural resources left
  - The exhaustion of **cheaply accessible fossil fuels** is highly likely to affect all societies in dramatic ways
- A fourth candidate is world capital investment
  - More investment means (or at least should lead to) more wealth
  - But also more pollution
- A fifth candidate is the percentage of capital invested in the agricultural sector
  - Part of the available capital must be invested in growing the food we need to survive as a species

Forrester's World2 SD Diagram

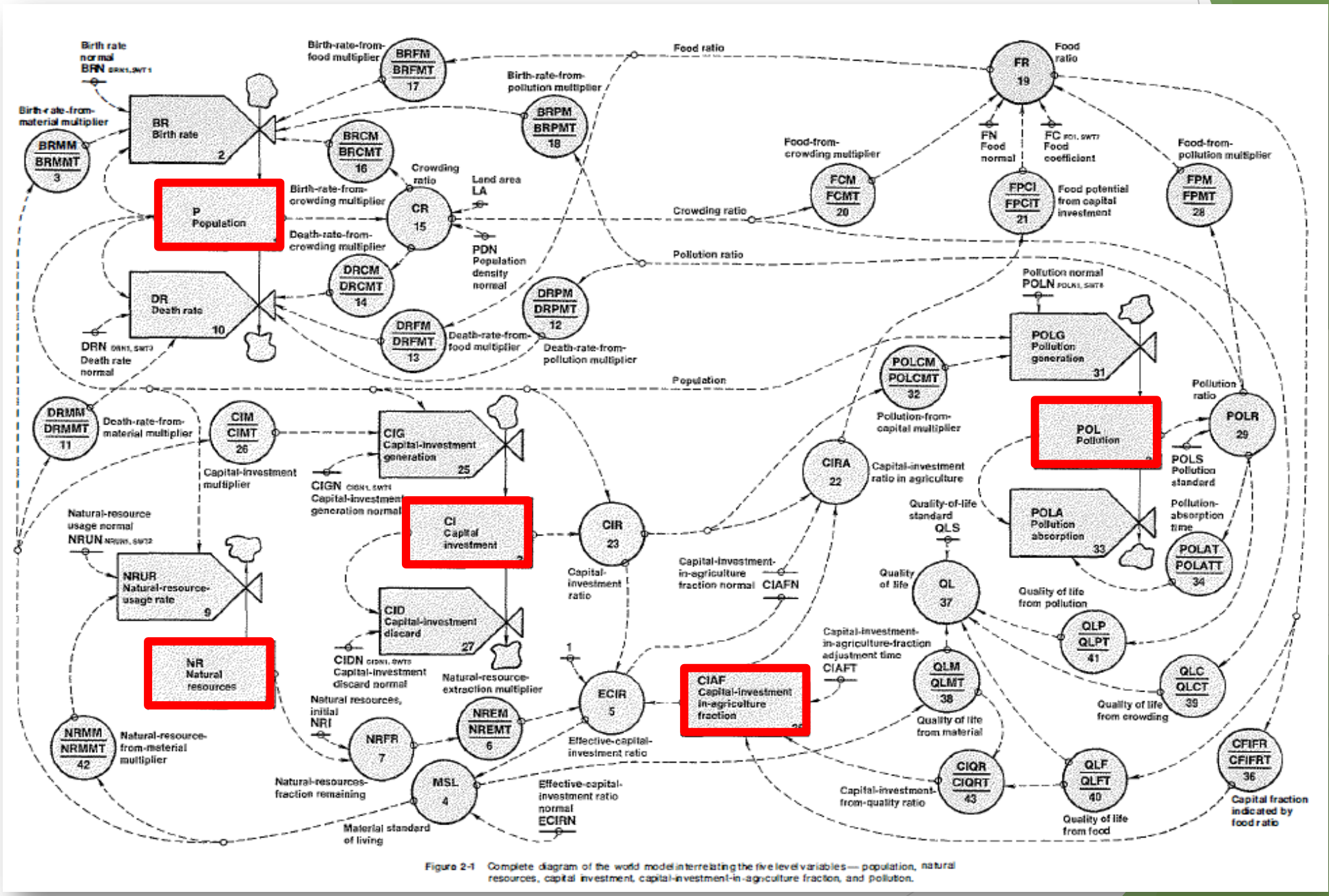


Figure 2-1 Complete diagram of the world model interrelating the five level variables — population, natural resources, capital investment, capital-investment-in-agriculture fraction, and pollution.

Selection of Rate Variables and Laundry Lists

- Each **state variable** was given a rate with a single inflow and a single outflow
- **Example:** State Variable: **Population**, Inflow: **Birth Rate**
- The Laundry List of variables affecting the **Birth Rate** postulated in World2 is:

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

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

$$Birth_rate = Population \cdot f\,(Pollution, Food, Crowding, Material_Standard_of_Living)$$

Selection of Rate Variables and Laundry Lists

- Functions of four (and more) variables are difficult to identify
- 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
- Forrester then applied an old trick: **The small signal approximation**
  - Defined the values of all variables in year 1970 as "normal values"
  - Took these normal values out, as parameters
  - Formulated static tabular functions as deviations from the norm

$$Birth_rate = BRN \cdot Population \cdot f_{1n}(Pollution) \cdot f_{2n}(Food) \cdot f_{3n}(Crowding) \cdot f_{4n}(Material_Standard_of_Living)$$

Rate Variables and Laundry Lists

- **Example**: Impact of Standard of Living on the Birth Rate

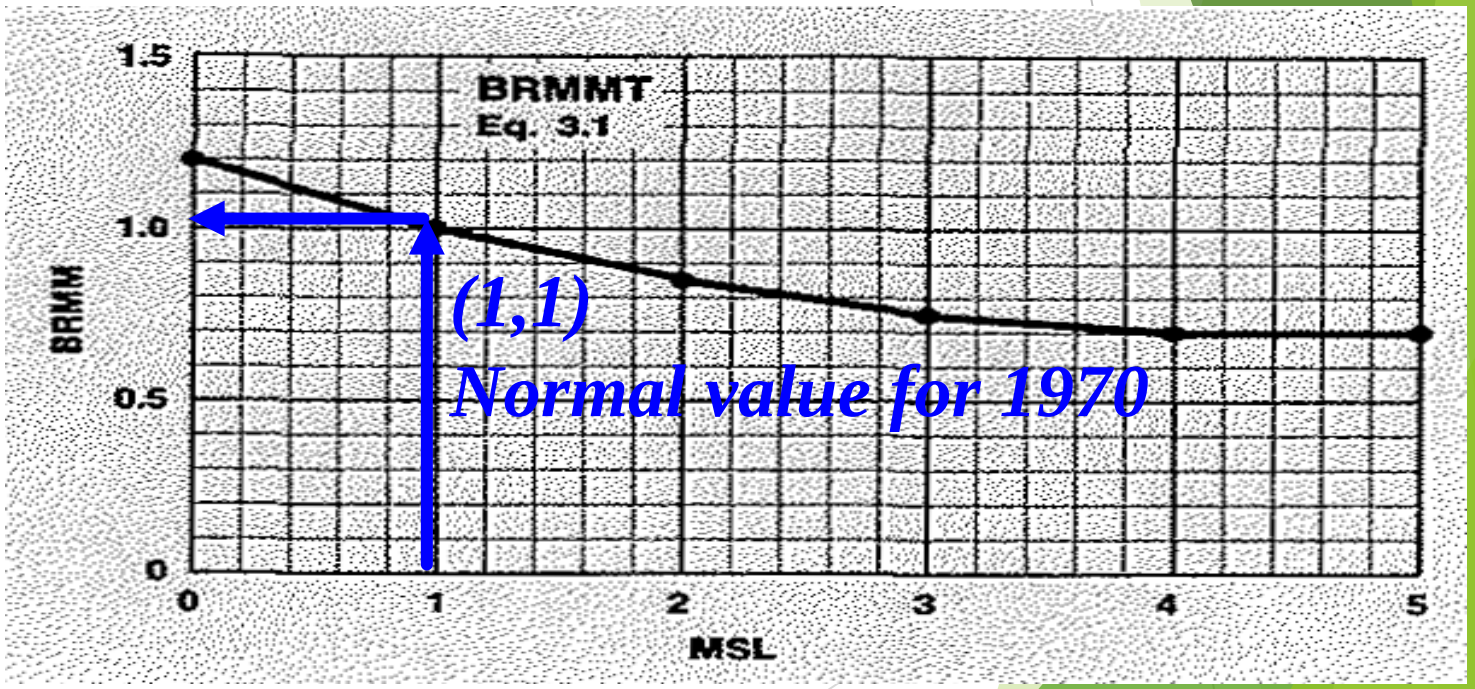
$$Birth_rate = BRN \cdot Population \cdot f_{1n}(Pollution) \cdot f_{2n}(Food) \cdot f_{3n}(Crowding) \cdot f_{4n}(Material_Standard_of_Living)$$

$BRN\ 1970 = 0.04$

$Population\ 1970 = 1.6\ 10^9$

$f_{4n}(Material_Standard_of_Living)$

Rationale: "*birth rate in third world nations with a low living standard is higher than in more developed countries*"



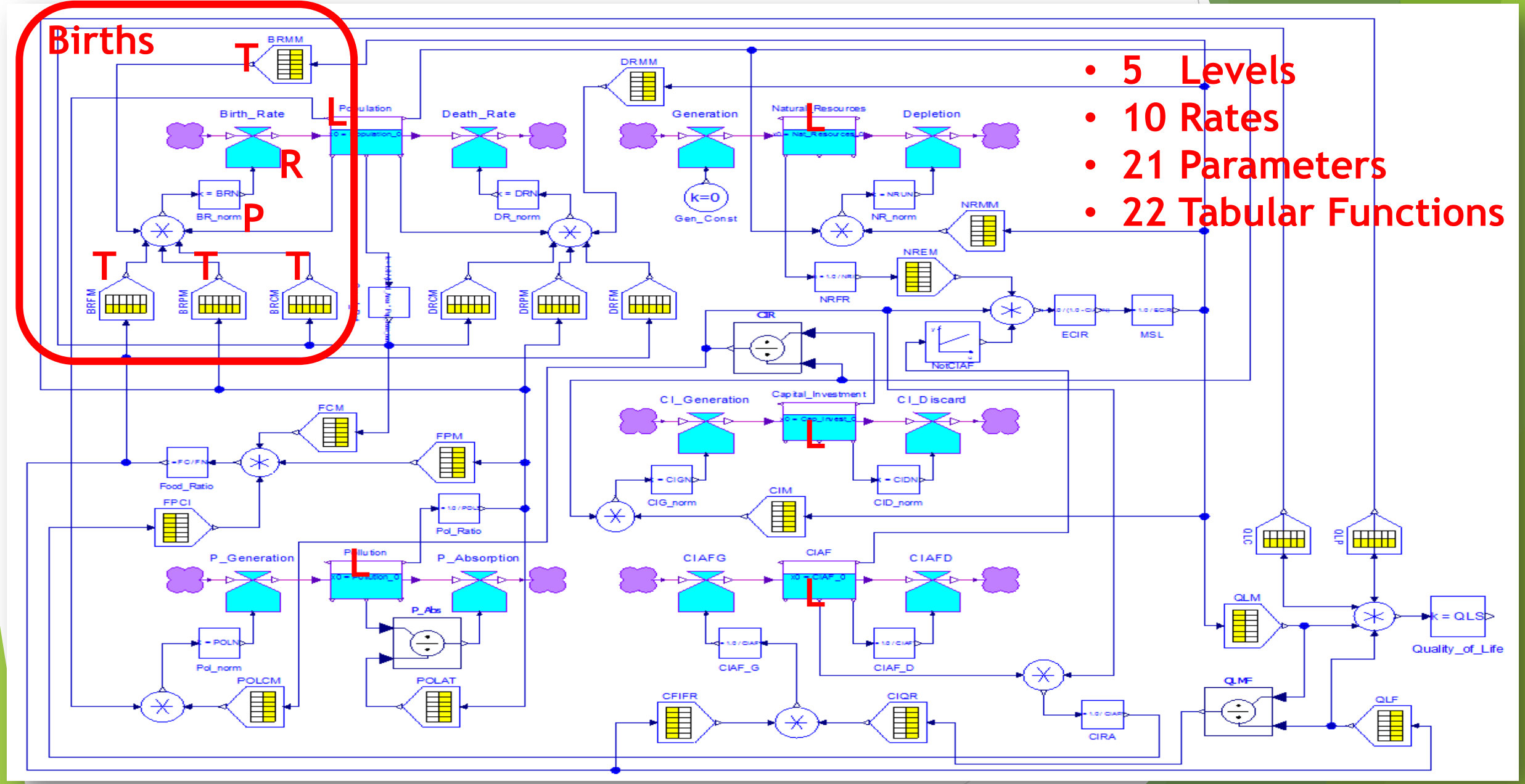
Forrester, J. World Dynamics, 2nd Ed, 1973. pg. 35

Rate Variables and Laundry Lists

- The obvious methodological risks were perfectly known by Forrester at the time
- "*High standard of living is usually associated with a higher adequacy of food, more crowding, and more pollution.*
  These effects have probably not been reliably disentangled.
  It is doubtful that they could be separated on the basis of available data and data-analysis techniques.
  But because the kinds of conclusions that one is entitled to draw from dynamic models are usually not sensitive to most parameter values, we can proceed on the expectation that a reasonable estimate is sufficient"
- What is "reasonable" and what is "sufficient" in the domain of long term world affairs projections ?
  - Important question after having embraced a small signal approximation approach !
- System Dynamics-based world modelers must be fully aware of these issues before moving forward

One definition for "complexity"

The World as Levels, Rates, Parameters, Tabular Functions



- 5 Levels
- 10 Rates
- 21 Parameters
- 22 Tabular Functions

World2, full system, all variables (original)

P	Population
BR	BirthRate
BRMM	Birth-Rate-from-Material Multiplier
MSL	MaterialStandardofLiving
ECIR	Effective-Capital-InvestmentRatio
NREM	Natural-Resource-Extraction Multiplier
NRFR	Natural-ResourceFractionRemaining
NR	NaturalResources
NRUR	Natural-Resource-UsageRate
DR	DeathRate
DRMM	Death-Rate-from-Material Multiplier
DRPM	Death-Rate-from-Pollution Multiplier
DRFM	Death-Rate-from-Food Multiplier
DRCM	Death-Rate-from-Crowding Multiplier
CR	CrowdingRatio
BRCM	Birth-Rate-from-Crowding Multiplier
BRFM	Birth-Rate-from-Food Multiplier
BRPM	Birth-Rate-from·Pollution Multiplier
FR	FoodRatio
FCM	Food-from-Crowding Multiplier
FPCI	FoodPotentialfromCapitalInvestment
CIRA	Capital-InvestmentRatioinAgriculture

CIR	Capital-InvestmentRatio
CI	CapitalInvestment
CIG	Capital-InvestmentGeneration
CIM	Capital-Investment Multiplier
CID	Capital·InvestmentDiscard
FPM	Food-from-Pollution Multiplier
POLR	PollutionRatio
POL	Pollution
POLG	PollutionGeneration
POLCM	Pollution-from·Capital Multiplier
POLA	PollutionAbsorption
POLAT	Pollution·AbsorptionTime
CIAF	Capital-Investment-in·AgricultureFraction
CFIFR	CapitalFractionIndicatedbyFoodRatio
QL	QualityofLife
QLM	QualityofLifefromMaterial
QLC	QualityofLifefromCrowding
QLF	QualityofLifefromFood
QLP	QualityofLifefromPollution
NRMM	Natural-Resources-from-Material Multiplier
CIQR	Capital-Investment-from-QualityRatio

Statistical Year Books

- Statistical Year Books were used to propose sensible functional relationships for the static tabular functions
- 22 of such functions in World2

	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 rate 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

Sector	Rates (+),(-)	Equations
Population		$Birth_Rate = Population \cdot BRN \cdot BRCM \cdot BRFM \cdot BRMM \cdot BRPM$
Agric.		$CIAFD = \frac{CIAF}{CIAFT}$
		$CIAFG = \frac{CFIFR \cdot CIQR}{CIAFT}$
Capital		$CI_Discard = CIDN \cdot Capital_Investment$
		$CI_Generation = CIGN \cdot CIM \cdot Population$
Population		$Death_Rate = Population \cdot DRN \cdot DRCM \cdot DRFM \cdot DRMM \cdot DRPM$
Nat. Res.		$Depletion = Population \cdot NRUN \cdot NRMM$
Pollution		$P_Absorption = \frac{Pollution}{POLAT}$
		$P_Generation = Population \cdot POLN \cdot POLCM$

We will see that these needed to be added in Mod-SD (not defined explicitly as Rates in the original model)

Hints

N: Normal 1970
M: Mult. Factor
T: Time Constant

Level
Rate

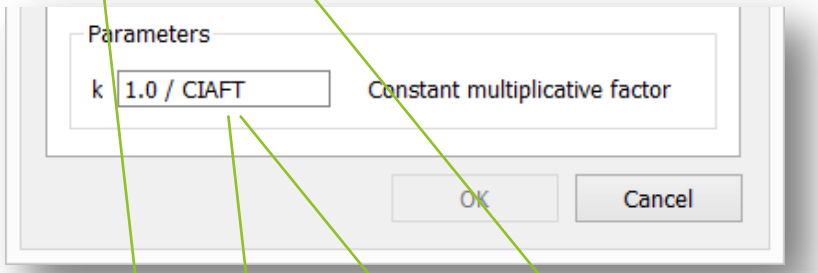
D: Decrease Rate
G: Growth Rate

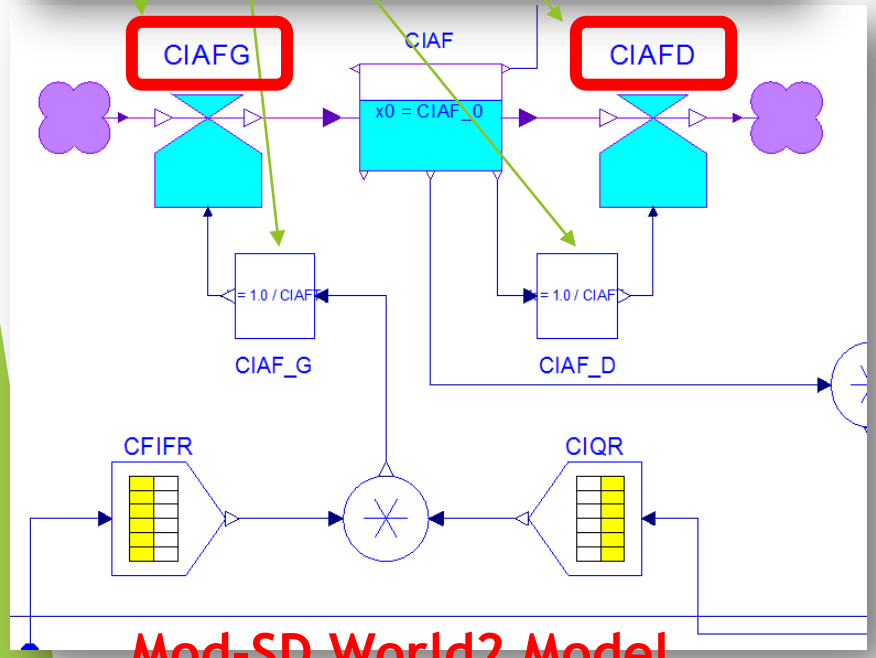
Careful ! CIAF*D* and CIAF*G* "added" as Rates

Level: Capital Investment In Agriculture Fraction

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

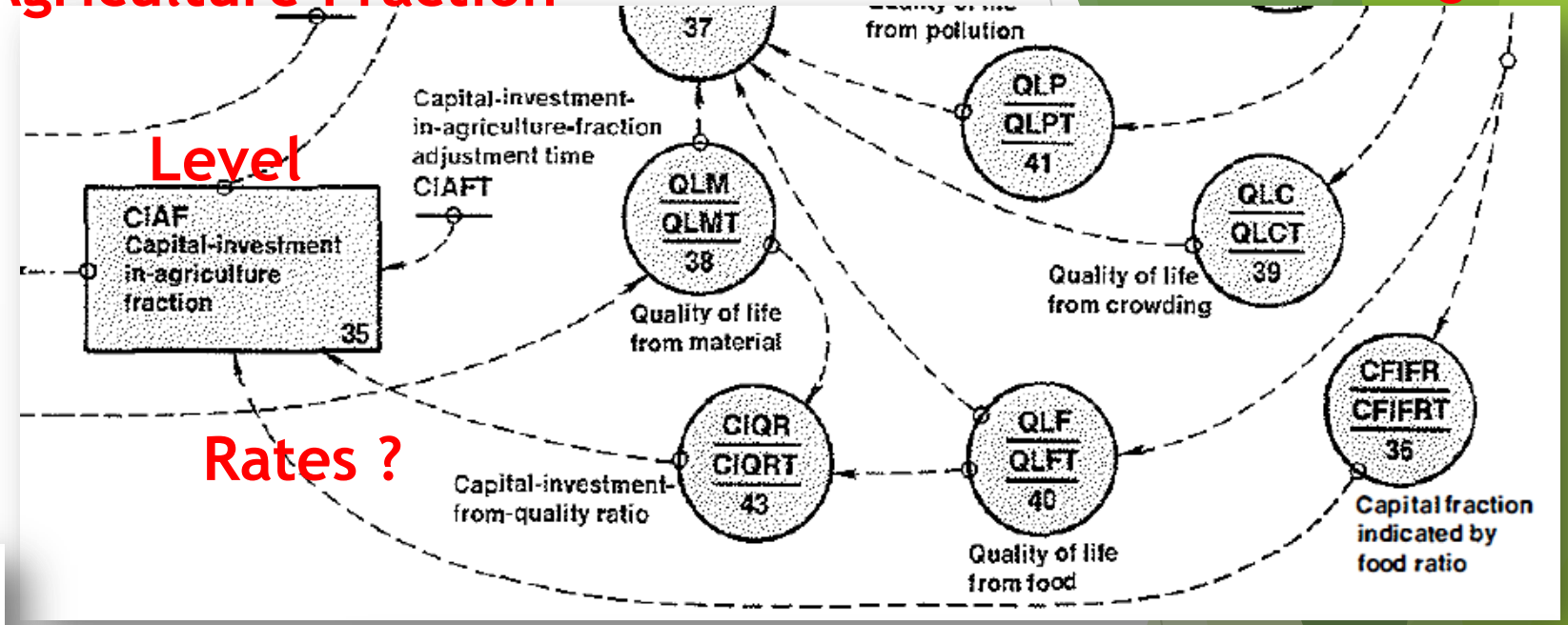
$$CIAFG = \frac{CFIFR \cdot CIQR}{CIAFT}$$





Mod-SD World2 Model

Forrester's World2 Diagram




```
CIAF.K=CIAF.J+(DT/CIAFT)(CFIFR.J*CIQR.J-CIAF.J)        35, L
CIAF=CIAFI                                             35.1, N
CIAFI=.2                                               35.2, C
CIAFT=15                                               35.3, C
```

time + -

```
   CIAF    - CAPITAL-INVESTMENT-IN-AGRICULTURE FRACTION
             (DIMENSIONLESS)
   CIAFT   - CAPITAL-INVESTMENT-IN-AGRICULTURE-FRACTION
             ADJUSTMENT TIME (YEARS)
   CFIFR   - CAPITAL FRACTION INDICATED BY FOOD RATIO
             (DIMENSIONLESS)
   CIQR    - CAPITAL-INVESTMENT-FROM-QUALITY RATIO
             (DIMENSIONLESS)
   CIAFI   - CAPITAL-INVESTMENT-IN-AGRICULTURE FRACTION,
             INITIAL (DIMENSIONLESS)
```

World Dynamics, 2nd Ed, 1973. pg. 59

Auxiliary Variables

$$CIR = \frac{Capital_Investment}{Population}$$

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

$$Crowding_Ratio = \frac{Population}{Land_Area \cdot Pop_dens_norm}$$

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

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

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

$$NRFR = \frac{Natural_Resources}{NRI}$$

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

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

$$Quality_of_Life = QLS \cdot QLC \cdot QLF \cdot QLM \cdot QLP$$

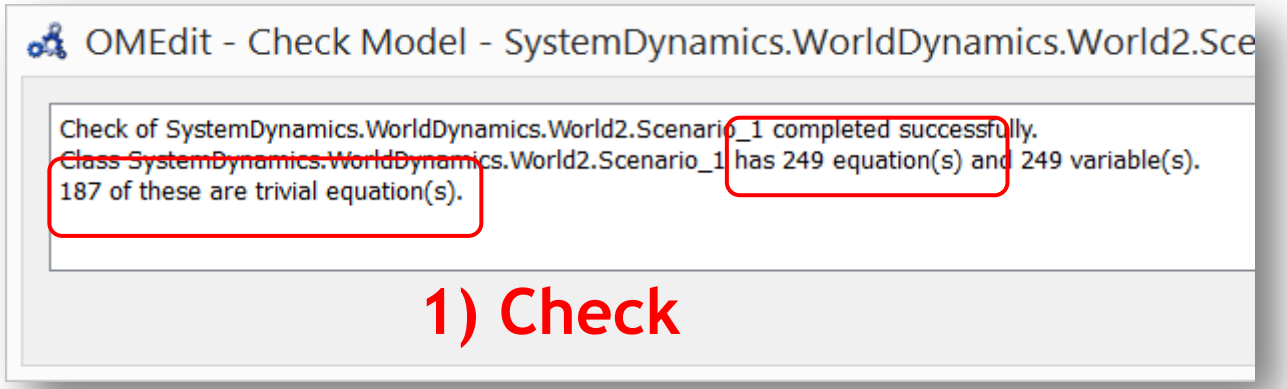
Values for Parameters and Initial Conditions

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

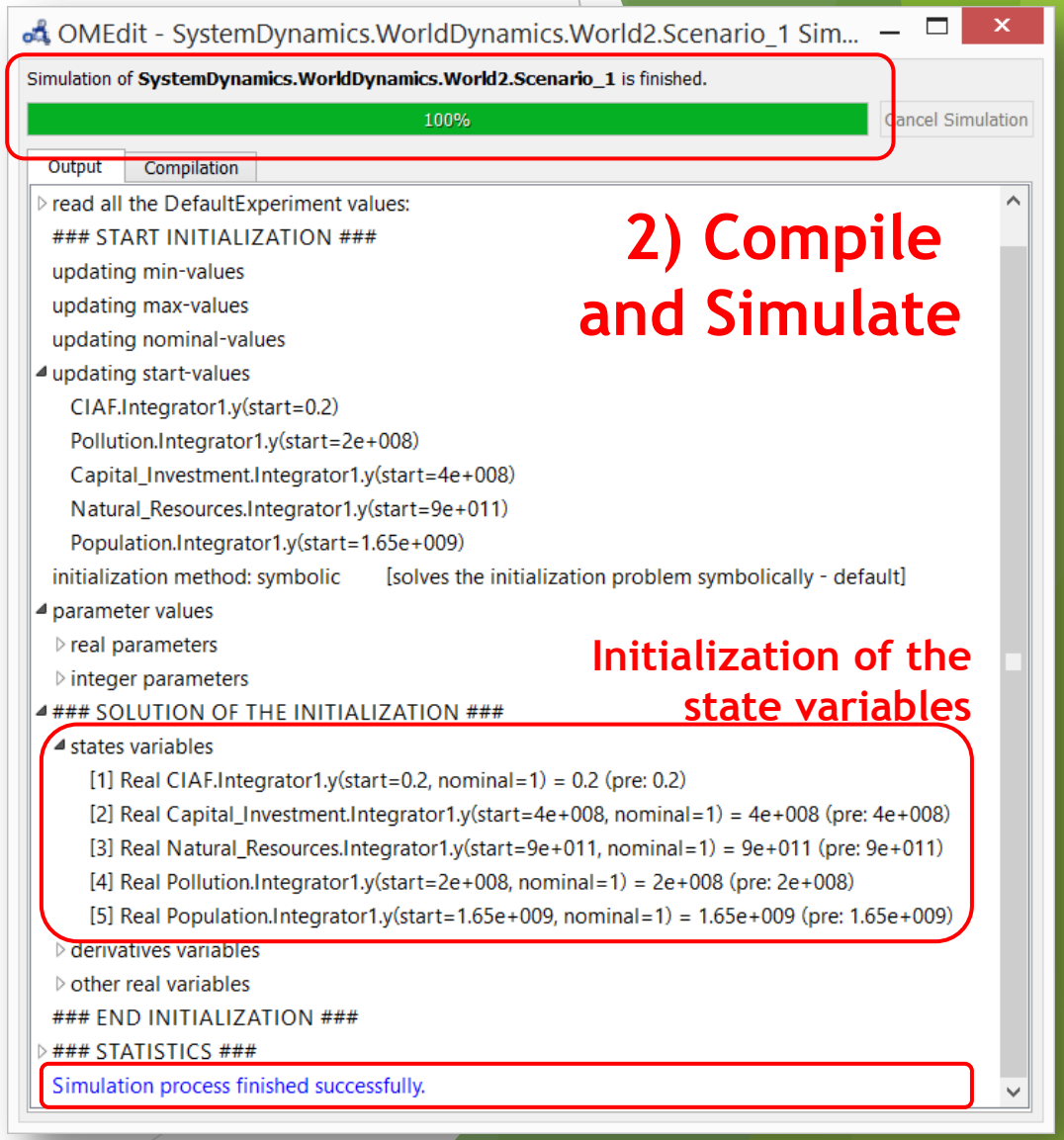
$$Population = 1.65 \cdot 10^9$$
$$Pollution = 2.0 \cdot 10^8$$
$$Natural_Resources = 9.0 \cdot 10^{11}$$
$$Capital_Investment = 4.0 \cdot 10^8$$
$$CIAF = 0.2$$

Model Check and Compilation

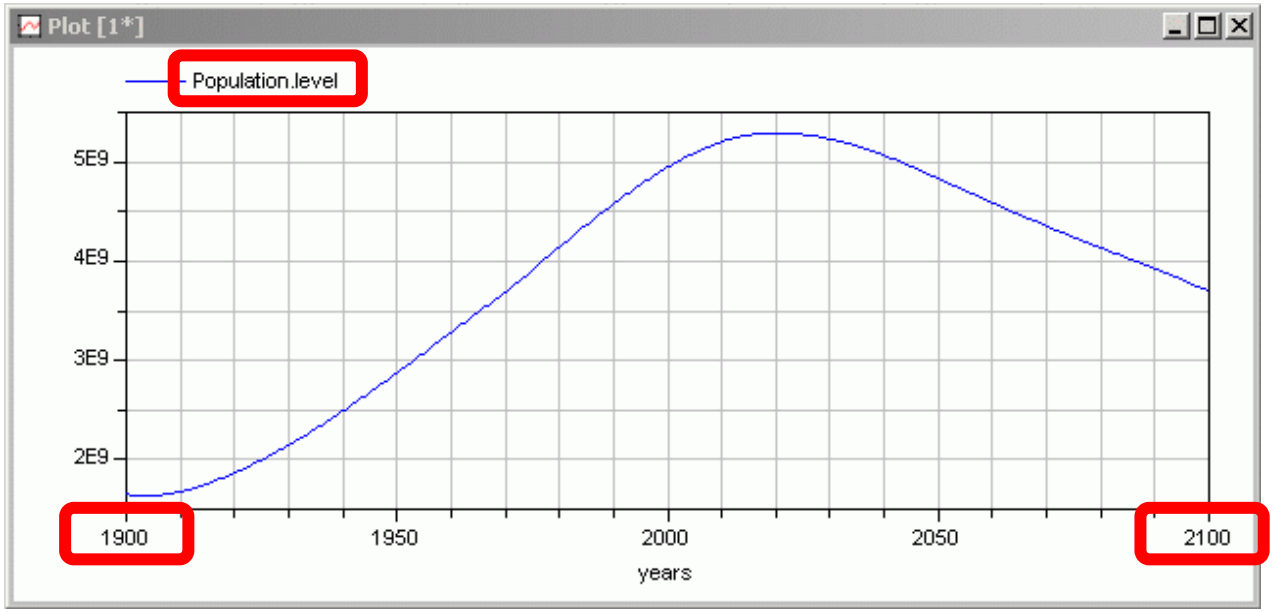
- Only 63 non-trivial equations

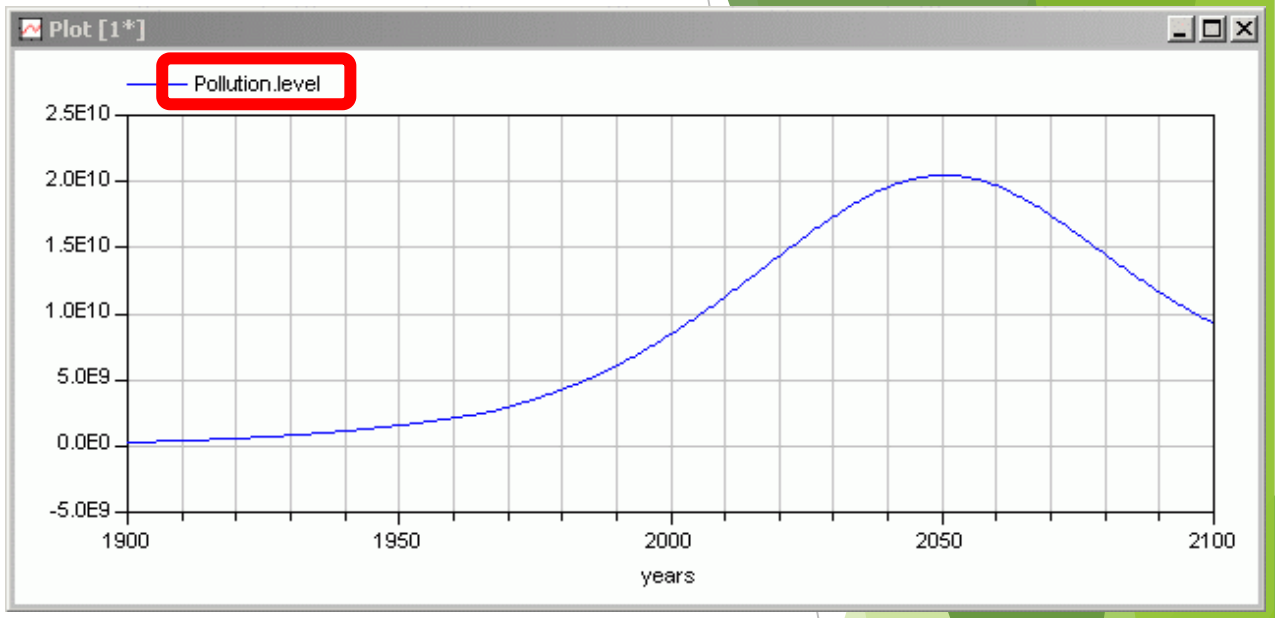


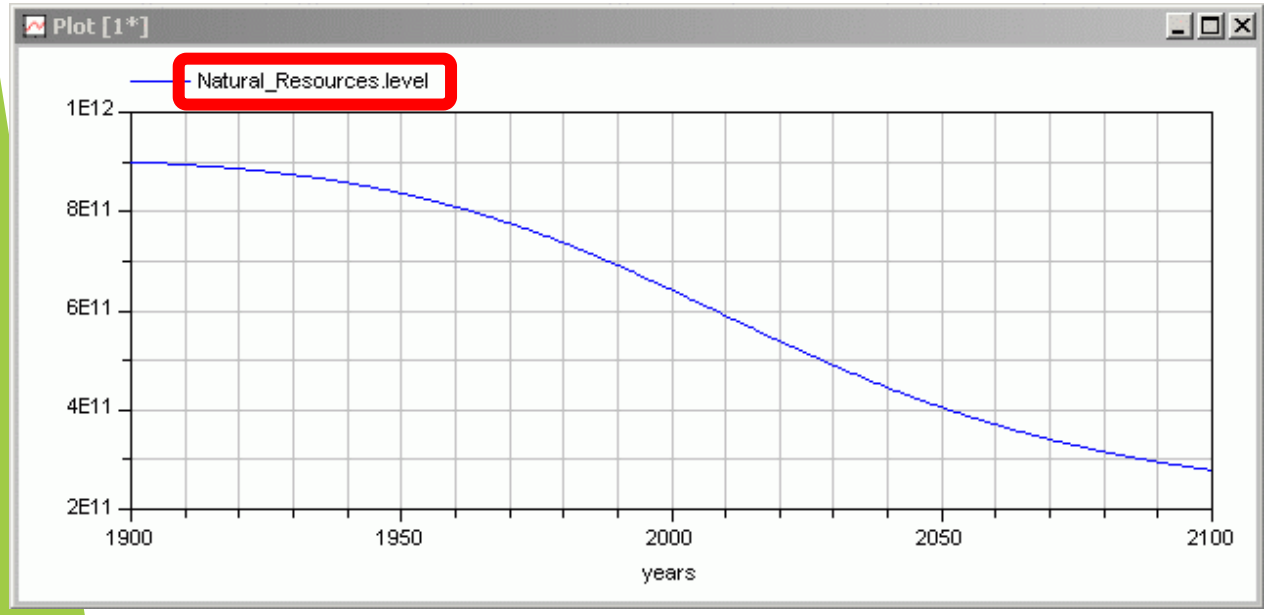
- System Dynamics produced a lot of system structure for a modest number of equations
  - Why not working with the equations directly ?

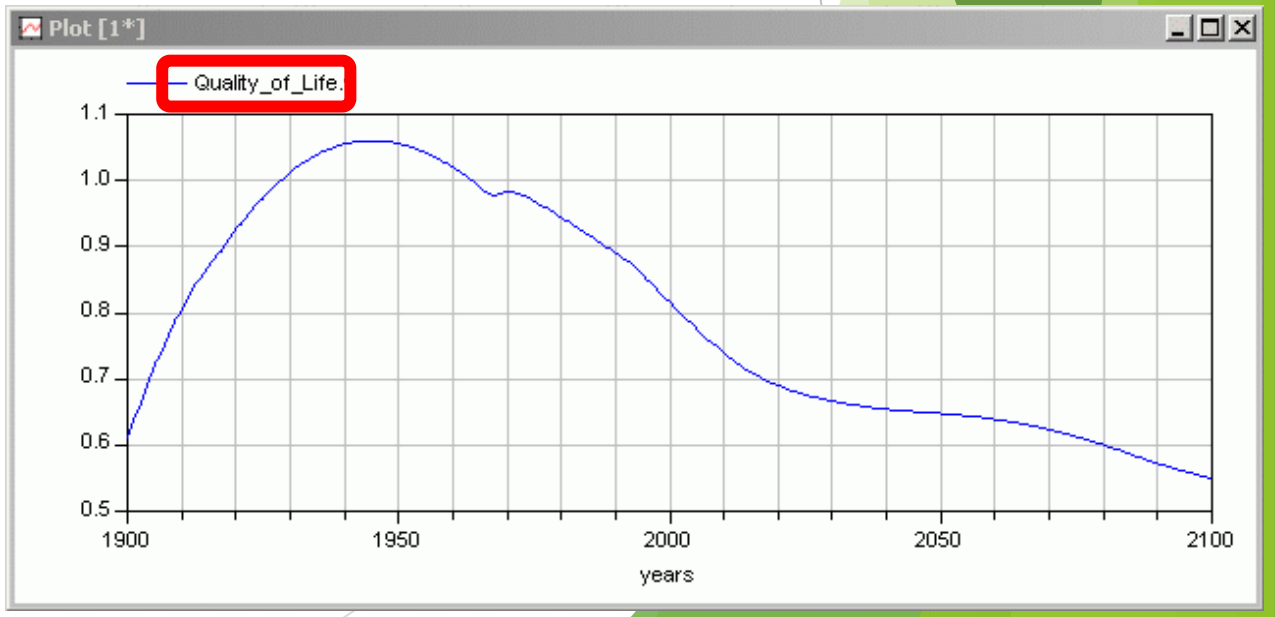


Simulation Results: Scenario 1 (Standard Run)

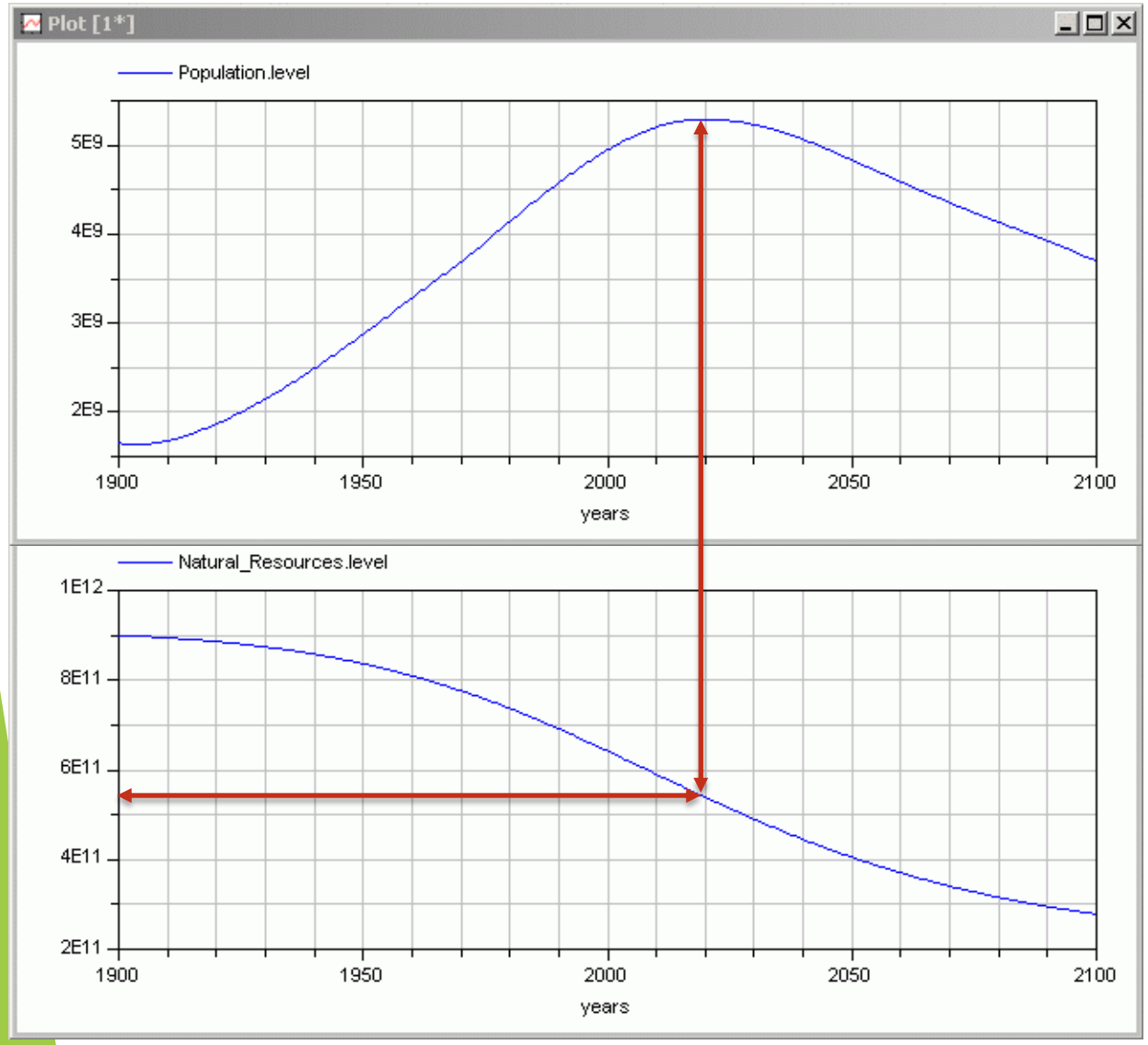








Simulation Results: Scenario 1 (Standard Run)



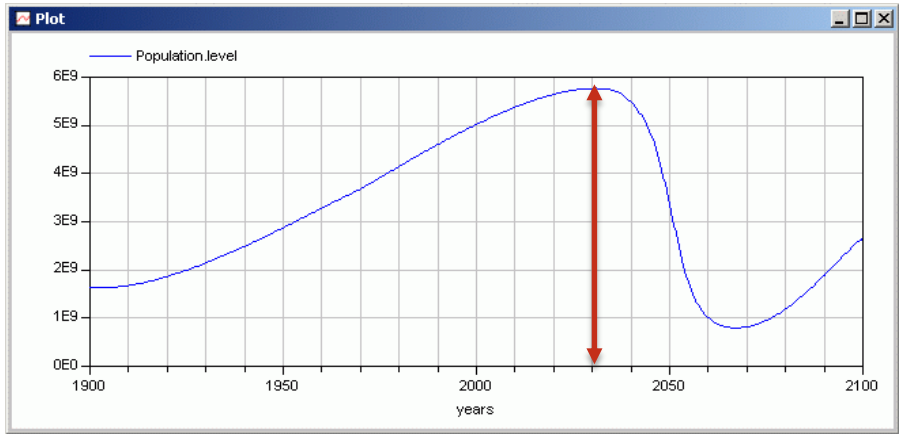
This model clearly exhibits a mode in which ***limits to growth*** have an important effect in the time window studied.

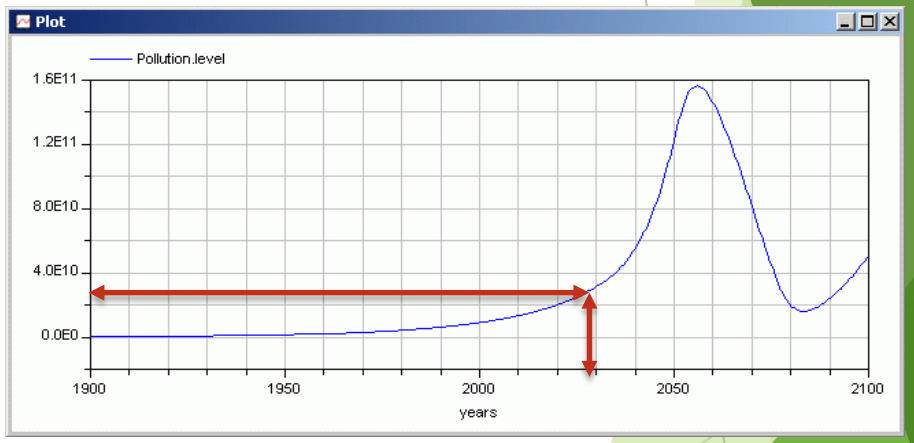
Population peaks at about the year 2020 with a little over 5 billion people.

As the natural resources shrink to a level below approximately $5 \cdot 10^{11}$, this generates a strong damping effect on the population.

Modifications suggested: Scenario 2 (More Nat. Resources)

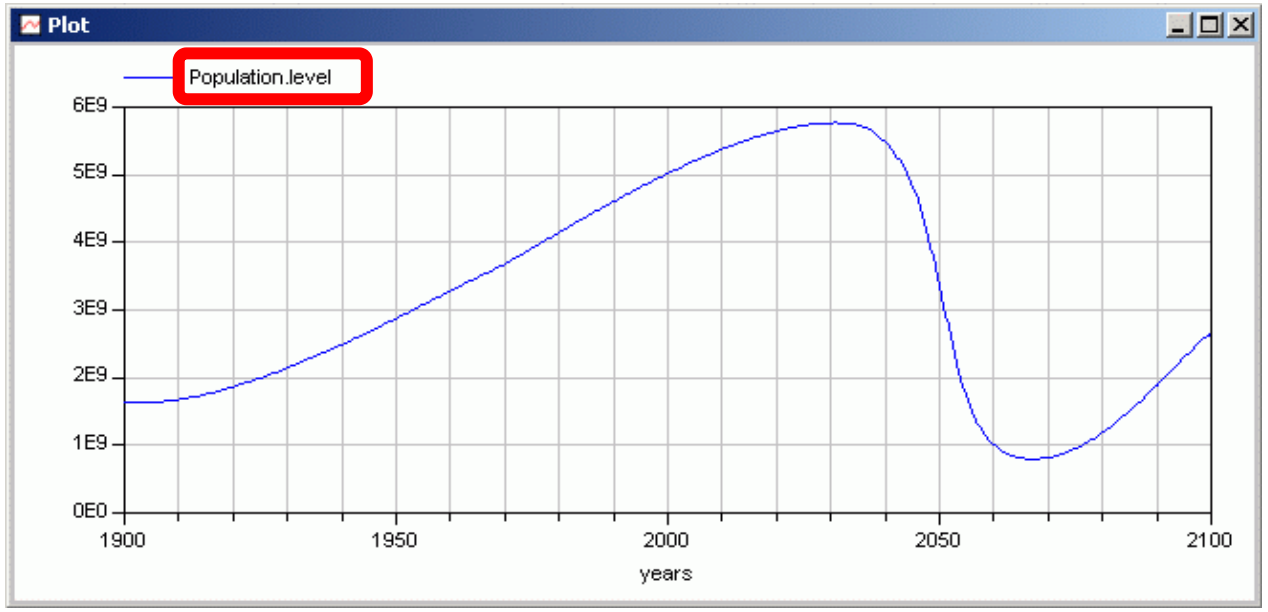
- Forrester proposed several experiments
- The first one is to reduce the usage of the natural resources by a factor of 4, starting with the year 1970
  - The effect of this modification is approximately the same as saying that more resources are available than anticipated. This is indeed true.
  - Now,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

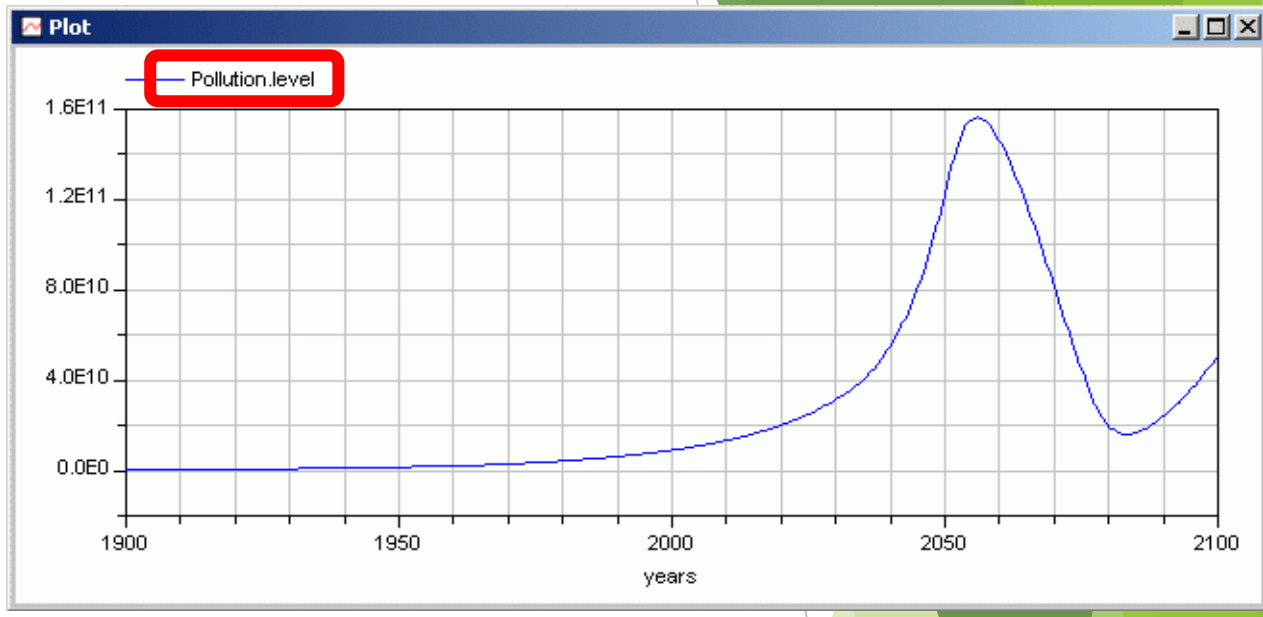


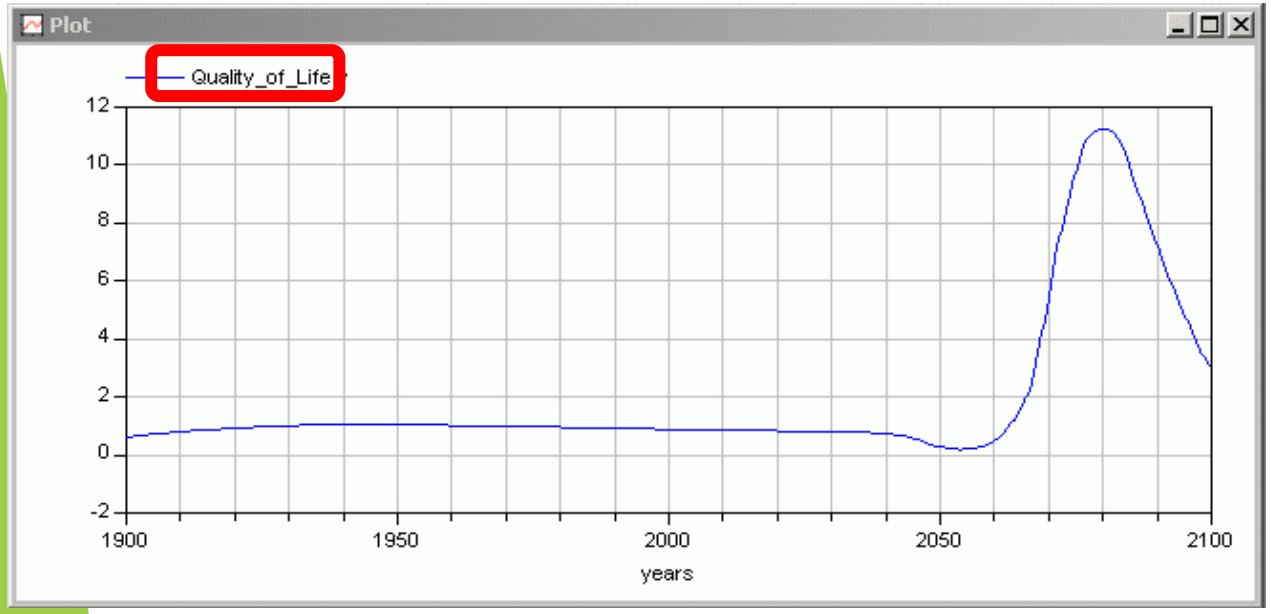


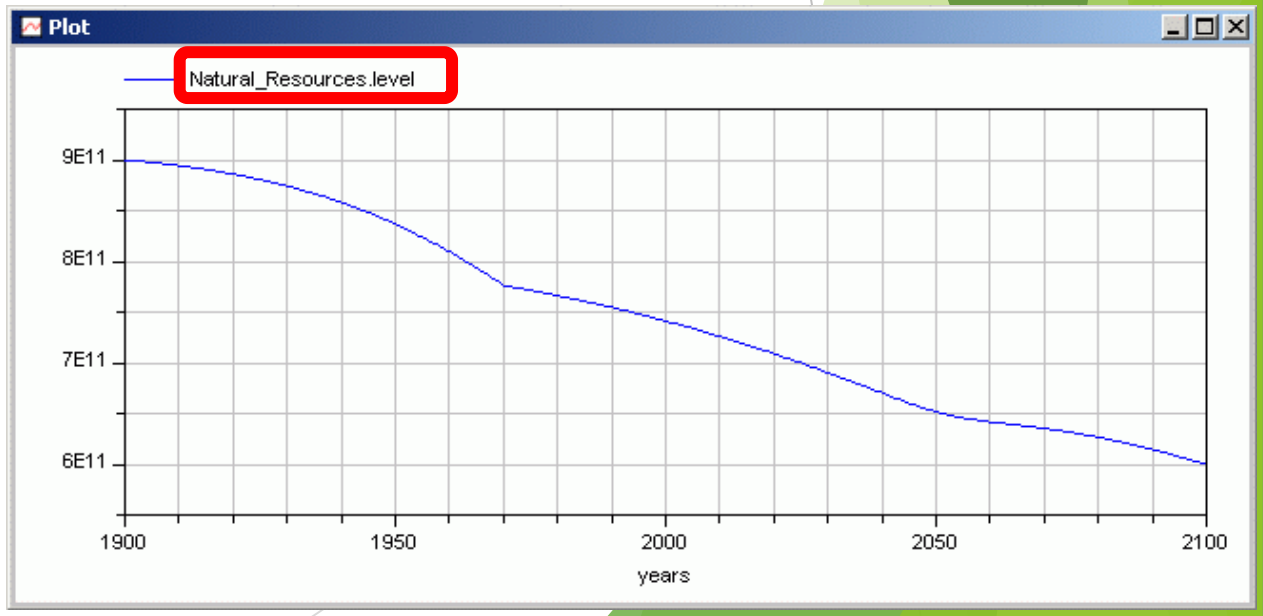
- This time around, the population peaks around the year 2035 at a level of approximately 5.8 billion people.
- The pollution is now what reaches a critical level. The natural resources are not depleted until after the year 2100.

Modifications suggested: Scenario 2 (More Nat. Resources)









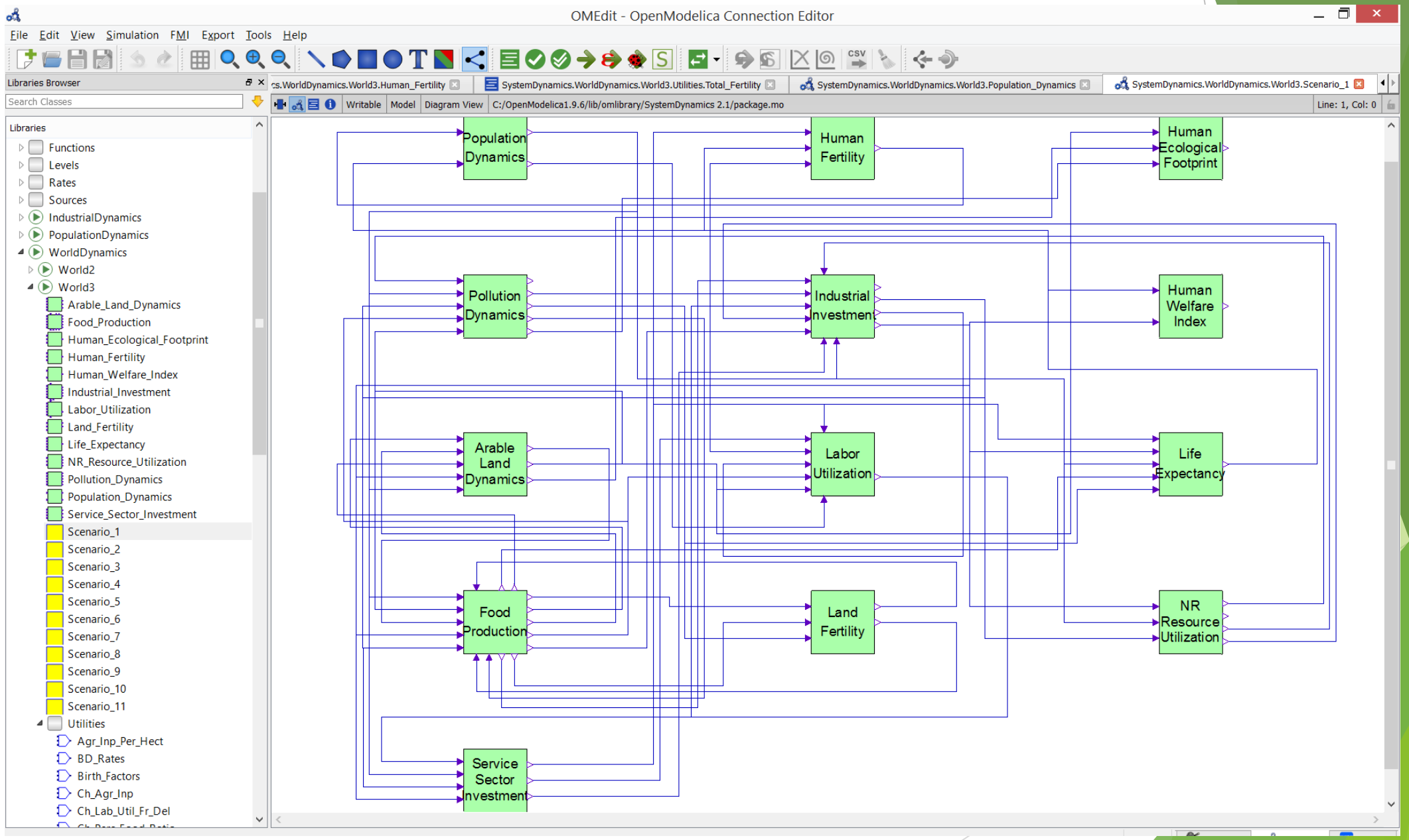
Other modifications

- Forrester thus proposed another modification.
  - Scenario 3: Additionally reduce the production of pollution by a factor of 4, starting with the year 1970. It postpones noticeably the population collapse.
- In Mod-SD we have available three additional default scenarios:
  - Scenario 4: Death rate reduced in 1970 to better account for modern advances in medicine.
    - It reproduces better real population measurements.
  - Scenario 5: Simulate backwards in time to discuss model validation concepts.
    - Requires special modifications to the Level blocks.
  - Scenario 6: Starts out from Scenario 2 applying different levels of natural resources utilization.
    - Adds a performance index involving Quality of Life and Population gradient.
    - The experiments showing the best performance in the short term are those which lead to the worst performance in the long term.

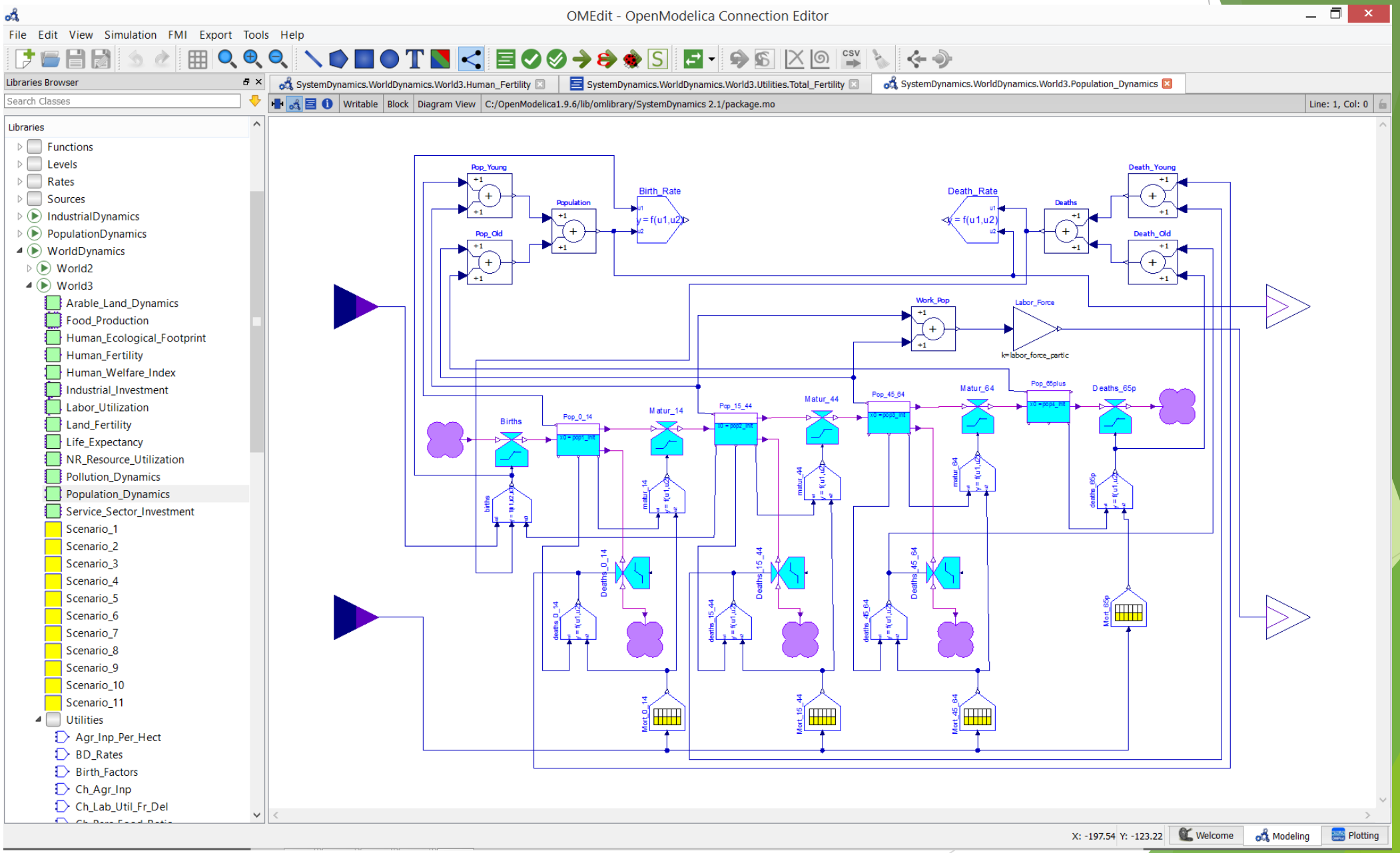
How Good Is The Model?

- 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 Mod-SD.

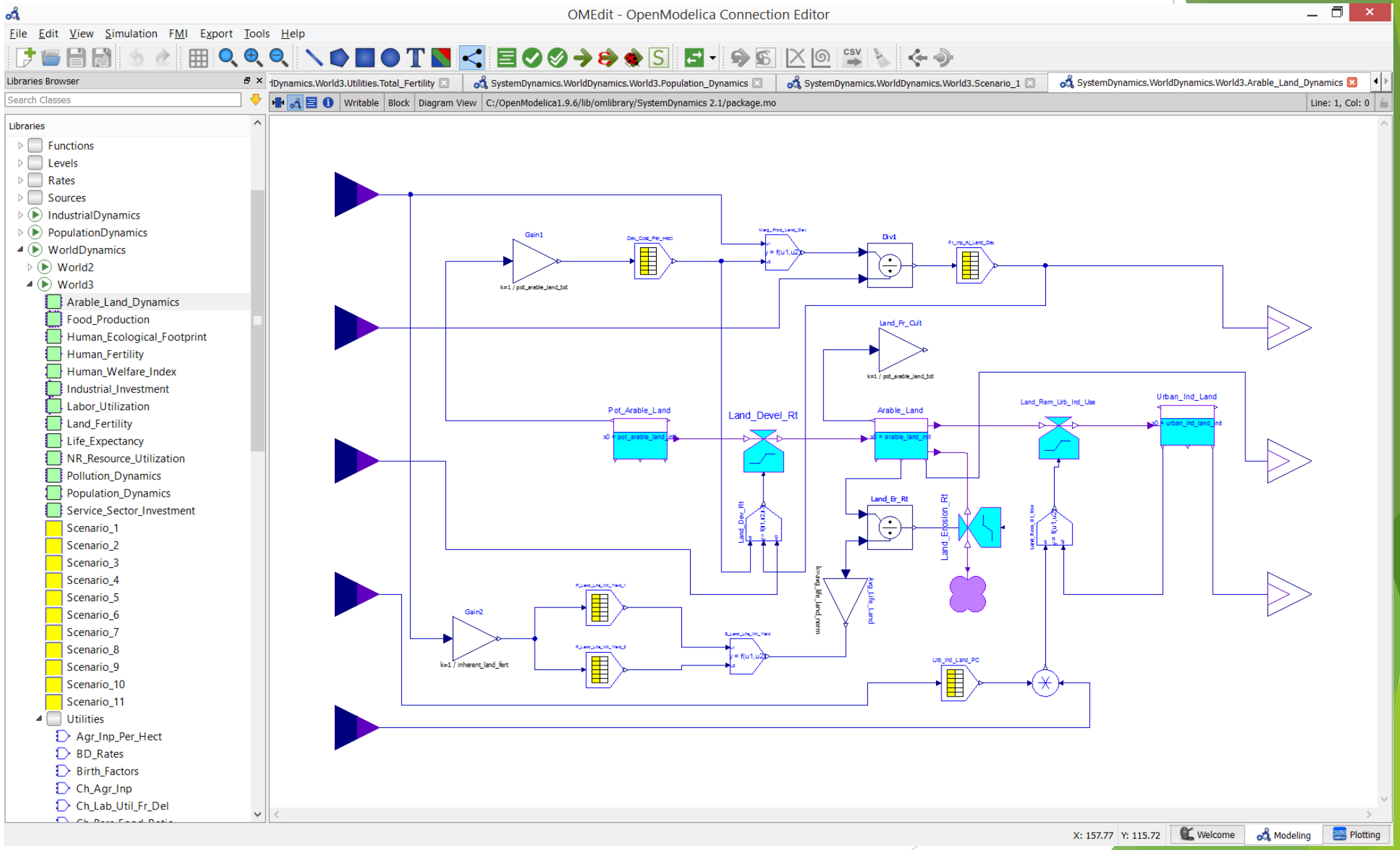
World3: Complete Model



World3: Population Dynamics

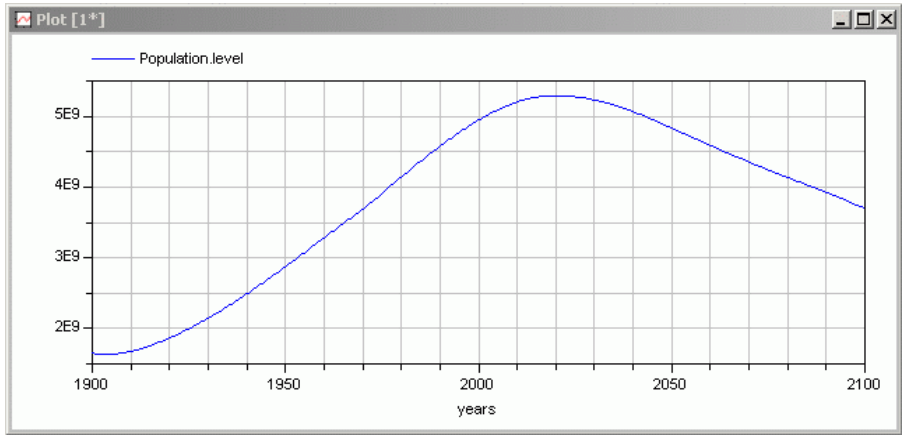


World3: Arable Land Dynamics

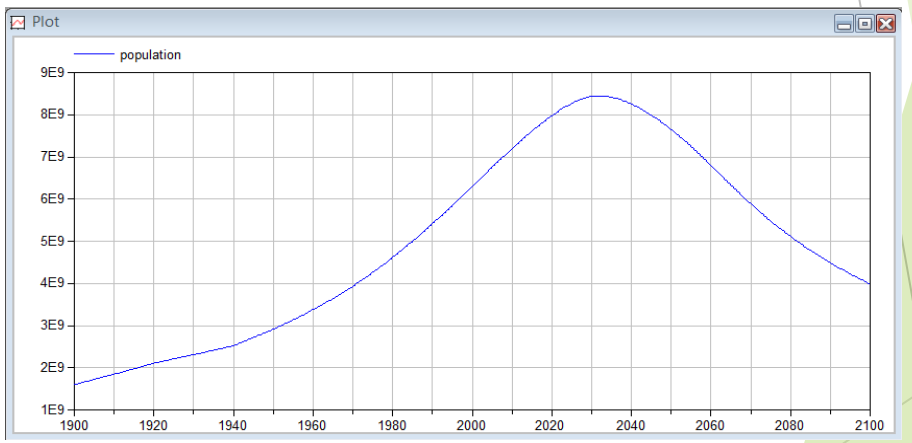


World2 and World3: Base Scenario (BAU)

- 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.



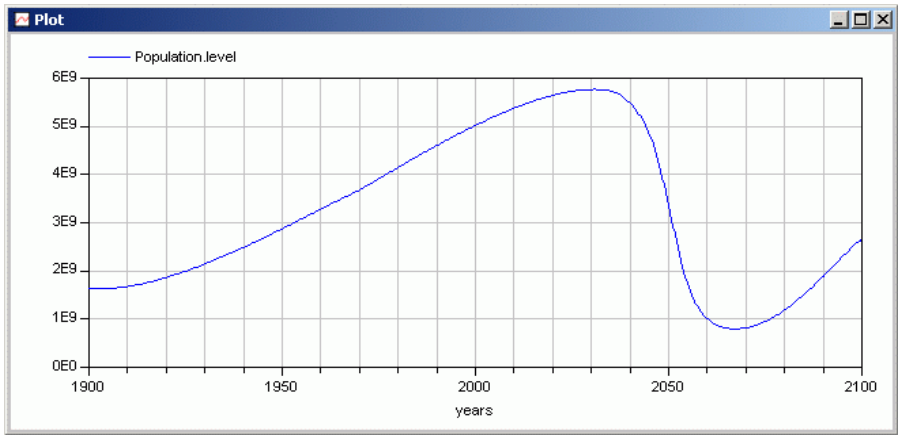
World2: Population



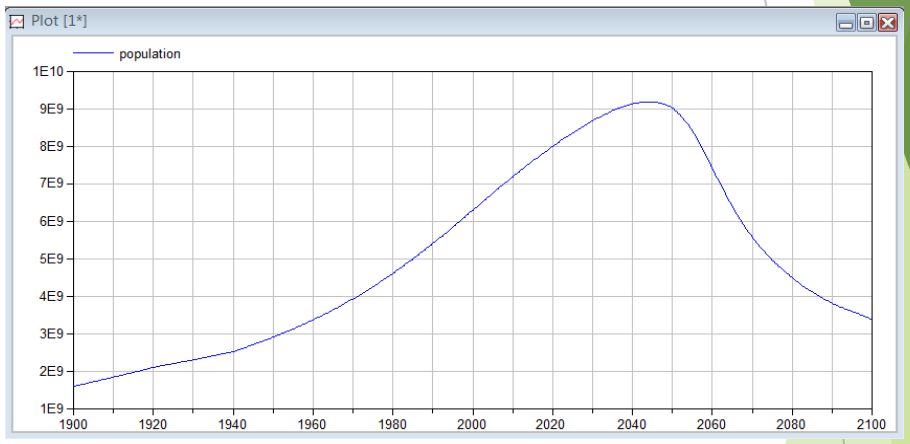
World3: Population

World2 and World3: More Energy Scenario

- 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.



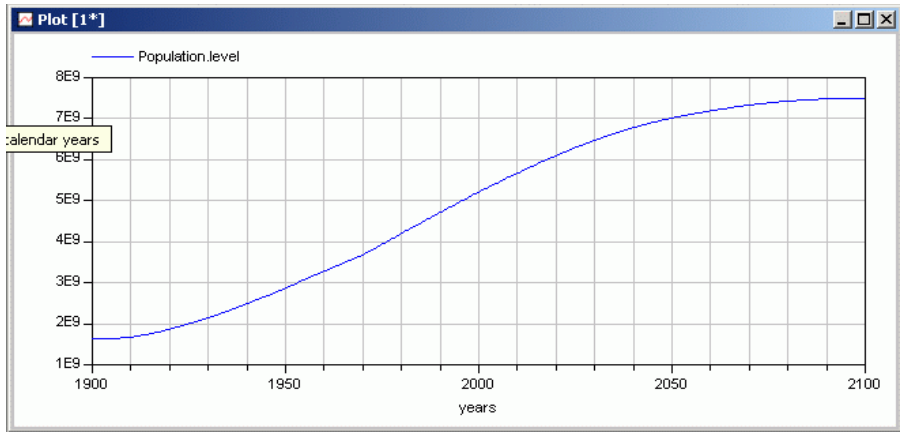
World2: Population



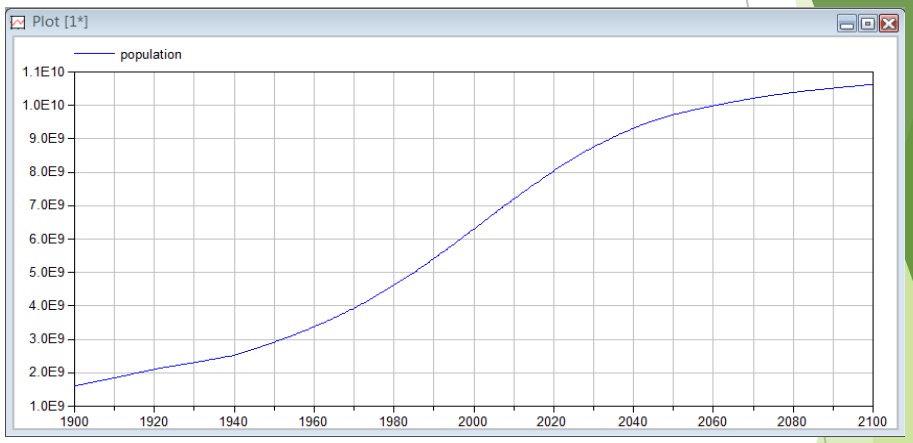
World3: Population

World2 and World3: Improved Scenario

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



World2: Population



World3: Population

Conclusions I

- 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 run so far show imminent limits to growth

Conclusions II

- 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, 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 GDP growing for a few more years, which with our current economic system can only be accomplished with a larger population.

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