International Journal of Development and Sustainability
ISSN: 2186-8662 – www.isdsnet.com/ijds
Volume 11 Number 11 (2022): Pages 348-366
ISDS Article ID: IJDS22083101

A *World3* analysis of the sensitivity of population/resource dynamics to pandemic-scale variation in life expectancy

Jack K. Horner *

Independent Researcher, Lawrence, Kansas, USA

Abstract

How do pandemics affect population/resource dynamics, and conversely? Canonical epidemiological models do not address nominally non-pandemic population/resource variables such as food production, industrial production, and pollution generation and thus cannot answer this question. Using a well-characterized population/resource dynamics simulator, *World3*, I compute the sensitivity of approximately 200 population/resource variables to pandemic-scale variation in life expectancy, for nine *World3* scenarios. These scenarios span regimes ranging from the practices and policies of the 20th century, to a sequence of scenarios that implement birth control and pollution controls, increase industrial and agricultural investment, and improve food production technology, resource conservation practices, and resource extraction efficiency. (Collectively, these scenarios constitute the de facto sensitivity-analysis baseline in the *World3* user community.) The results of this study suggest that the population/resource-management policies and practices of one of those scenarios can strongly mitigate the fiscal and physical disruption of some pandemics.

Keywords: Population/resource dynamics; pandemic dynamics; *World3*

Cite this article as: Horner, J.K. (2022), "A *World3* analysis of the sensitivity of population/resource dynamics to pandemic-scale variation in life expectancy", *International Journal of Development and Sustainability*, Vol. 11 No. 11, pp. 348-366.

* Corresponding author. *E-mail address:* jhorner@cybermesa.com

1. Introduction

In the epidemiological community, compartmental epidemiological models (Vynnycky and White, 2010) are the most common representation of population-disease dynamics. Such models represent the dynamics of disease in a population in terms of a small set of jointly exhaustive, mutually exclusive disease-state variables such as "Susceptible", "Infected", and "Recovering". These disease-state variables are generically called "compartments". In an epidemiological compartmental model, an individual in the population of interest has exactly one disease-state ("is in exactly one compartment") at a time. Compartmental epidemiological models are often informally classified and named by the listing the first letter of their disease-state variables, beginning with "S" (Susceptible). For example, in this informal taxonomy, a "SI" compartmental epidemiological model has just two compartments: "Susceptible" (S), and "Infected" (I). A "SEIRD" compartmental epidemiological model is a model that has "Susceptible" (S), "Exposed" (E). "Infected" (I), "Recovering" (R), and "Deceased" (D) compartments.

Compartmental epidemiological models evidently represent population-disease dynamics without regard to how those dynamics interact with nominally non-pandemic global population/resource factors such as food production, industrial production, capital investment, pollution generation, and non-renewable resource consumption. In order to assess the interaction between pandemic-, and population/resource-, dynamics, we need a model that integrates these regimes.

There is at least one immediate connection between the dynamics of compartmental epidemiological, and global population/resource dynamics, models. At the beginning of a global pandemic caused by a novel highly transmissible infectious agent, in the absence of effective control modalities (vaccination, masking, social distancing, etc.), the Susceptible (S) population is the world population.

1.1. Overview of *World3*

The *World3* simulator (Meadows et al., 1974; Cellier, 2008; Cellier, 2019; Wolfram, 2019) models, at a high level, the dynamical interaction of world population, pollution, agriculture, capital, non-renewable resources, and the effect of health services on life expectancy.

World3's behavior is well understood (Turner, 2014; Herrington, 2020). It evolved from the *Limits to Growth* project (Meadows et al., 1972), launched in the early 1970s. The objective of the *Limits to Growth* project was to determine whether systems analysis techniques developed by Jay Forrester and colleagues at MIT "could provide new perspectives on the interlocking complex of costs and benefits inherent in continued physical growth on a finite planet" (Meadows et al., 1974, p. vii).

In the first two decades of its existence, the *Limits to Growth* family of world dynamics simulators was extensively criticized (Simon and Kahn, 1984; Simon, 1996; Cole et al., 1973). More recent assessments (Turner, 2008; Turner, 2014; Randers, 2012; Nørgård et al., 2010; Herrington, 2020), however, argue that *World3* (especially *World3*'s Benchmark Scenario 1; see Section 1.2 of this paper) has predicted the trajectories of the global population and food production well. Table 1 compares the population predictions of *World3*'s "Business as Usual" (BAU) scenario (see Scenario 1, Section 1.2) with UN estimates (United Nations, 2019) of the world population, 1980 to 2020.

Table 1. Comparison of some *World3's* population predictions (from the "Business as Usual" (BAU) Benchmark Scenario; see Section 1.2) with the UN estimates (United Nations, 2019). Population is rounded to two significant figures; percent difference is rounded to one significant figure.

Year	*World3* prediction of world population (billions, from BAU Scenario)	UN estimate of world population (billions)	Percent difference between *World3* prediction, and UN estimate, relative to UN estimate
1980	4.6	4.5	2
1990	5.4	5.3	2
2000	6.2	6.1	2
2010	7.1	7.0	1
2020	7.9	7.8	1

Similarly, Table 2 compares *World3*'s BAU Scenario predictions of world food production per capita per year[1] with UN estimates of that quantity.

Table 2. Comparison of *World3*'s Benchmark Scenario 1 ("BAU") prediction of world food production with UN estimates (Roser and Ritchie, 2022) of the same. Food production units are vegetable-equivalent kilocalories per person per year (see Meadows et al., 1974, p. 282, for a definition of this unit).

Year	*World3* prediction, Benchmark Scenario 1 ("BAU")	UN Estimate, normalized to *World3*'s 1970 prediction	Percent difference, relative to UN estimate
1970	384	384	0
1980	407	400	2
1990	425	416	2
2000	430	432	0.5
2010	416	448	7
2020	390	464[2]	16

The *World3* BAU Scenario food production per capita per year magnitudes evidently agree well with UN estimates of the same, 1970-2000. The BAU predictions for food production are somewhat more pessimistic than UN estimates for 2010 and 2020.

[1] Meadows et al. (1974) estimate that 230 kilograms vegetable-equivalent production per capita per year is required for survival.
[2] Predicted value. It does not take into account the effects of the COVID-19 pandemic or agricultural yield losses in sub-Saharan Africa. Collectively, these effects would likely reduce the UN estimate about 10%, (to about 420 vegetable-equivalent kilograms per person per year).

Herrington (2020) shows that current empirical data is broadly consistent with the *World3* projections, and that if major changes to the consumption of resources are not undertaken, *World3* predicts that economic growth will peak and then rapidly decline by around 2040.

World3 was originally written in DYNAMO (Pugh, 1963) and was batch-oriented. By 2004, *World3* had been ported to the STELLA modeling language (Richmond, 2013). Cellier (2008) is an object-oriented (Rumbaugh et al., 1999; Schlaer and Mellor, 1992; Smith, 1996) re-engineering of the 2004 (STELLA) version of *World3* to the Modelica (Open Modelica, 2019; The Modelica Organization, 2019) simulation language. Cellier (2019) is an adaptation of Cellier (2008) to the *SystemModeler* (Wolfram, 2019) simulation framework.

The logical design (Boehm, 1981, Section 5.4; Boehm et al., 2000, pp. 312-313) of *World3* can be found in Meadows et al. (1974). Much of the detailed physical design (Boehm, 1981, Section 5.4; Boehm et al., 2000, pp. 312-313) of Cellier (2019) can be found in the online documentation that accompanies Cellier (2019).

Cellier (2019) can be executed interactively under Wolfram's *SystemModeler* (Wolfram, 2019) or invoked from a *Mathematica* script (Wolfram, 2022). The combined *Mathematica* and System Modeler framework renders World3 extensible (i.e., the framework provides read and write access to World3's data structures, model-execution control, extensive visualization functionality, and support ports of applications written in the *Mathematica* framework to the C++ language).[3]

1.2. The *World3* Benchmark Scenarios

Meadows et al. (2004) describe, at a high level, nine *World3* scenarios that span regimes ranging from continuing the practices and policies of the 20th century (called the "Business as Usual" scenario (BAU), to a sequence of scenarios that increasingly diverges from the BAU through increasing:

- birth control and pollution controls
- industrial and agricultural investment
- food production technology
- resource conservation practices
- resource extraction efficiency

I will call these Scenarios "the *World3* Benchmark Scenarios" or "the Benchmark Scenarios" .4 Collectively, the Benchmark Scenarios provide a de facto baseline for analyzing the sensitivity of *World3* predictions to variations in *World3* parameters.[5] By default, the duration of each Benchmark Scenario spans simulated

[3] The combined *Mathematica/SystemModeler/World3* framework is characterized as "experimental" by the Mathematica v13.1 documentation (Wolfram, 2022).

[4] Which *World3* scenarios should be subsumed under the name "Benchmark" could be debated, but it's clear enough that the community of World3 users has found the nine nominated as "Benchmark" in this paper to be a convenient reference. Meadows et al. (2004) describe a 10th scenario, which is Scenario 9 with the sustainability policies of Scenario 9 introduced 20 years earlier. The 10th scenario of Meadows et al. (2004) is not included in the current study. Cellier (2019) includes a 10th and 11th scenario, neither of which identical to any of Scenarios 1-9. As implemented, in the *SystemModeler* framework, however, Scenarios 10 and 11 of Cellier (2019) will not compile on the platform described in Section 2 of this paper. For this reason, they were excluded from consideration in the present paper.

[5] Unless otherwise noted, the term "parameter" in this paper means a software entity whose value is user-settable and is kept constant for the duration of any given execution of a scenario.

calendar years 1900 - 2100.[6] Here is a high-level description of the Benchmark Scenarios. Details of these scenarios can be found in Meadows et al. (1974), Meadows et al. (2004), and Cellier (2019).

1.2.1. Benchmark Scenario 1 (the "business-as-usual" (BAU), scenario) (Meadows et al., 2004, pp. 168-171)

In Benchmark Scenario 1, human practices and policies continue without significant deviation from the those followed during most of the 20th century. As a result, population and production increases until growth is halted by increasingly inaccessible resources. Increasing investment is required to maintain resource flows. That investment, which must be re-directed from other sectors of the economy, leads to declining output of both industrial goods and services. The decline of industrial goods and services causes a reduction in the food supply and in health services, thereby decreasing life expectancy, resulting in a population "collapse" (nominally, a 50% reduction of population size in less than ~50 years) beginning calendar year 2040. Figure 1 shows population as a function of time in *World3* Benchmark Scenario 1. Figure 2 shows life expectancy as a function of time in that Scenario. Figure 3 shows food produced per capita as a function of time in that Scenario.

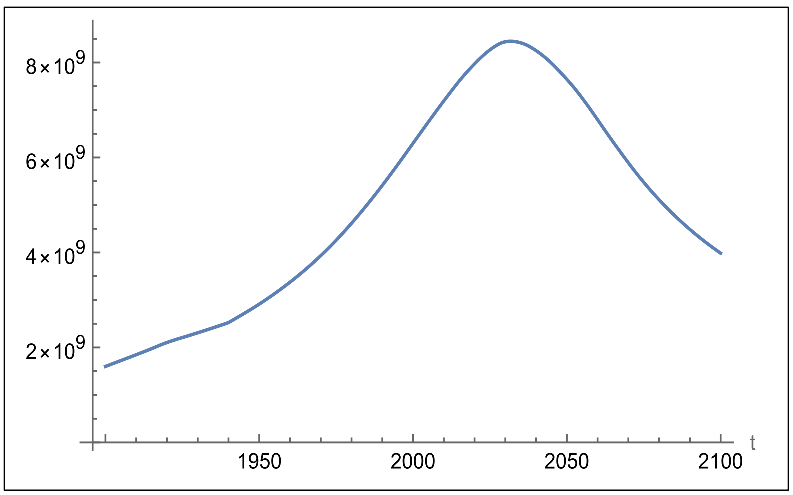

Figure 1. World population (number of persons) by time (Year). *World3*, Benchmark Scenario 1 ("Business as Usual")

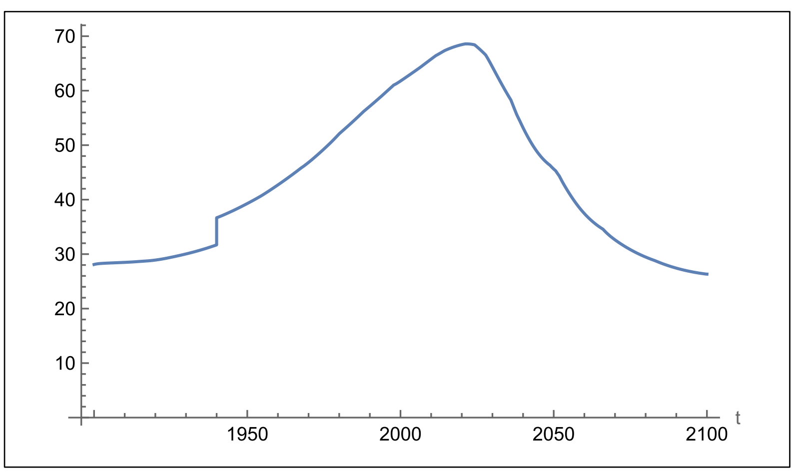

Figure **2.** World average Life Expectancy (in years) by time (Year). *World3*, Benchmark Scenario 1.

[6] Some *World3* predictions past Year 2100 likely lie well outside the calibration space of the simulator.

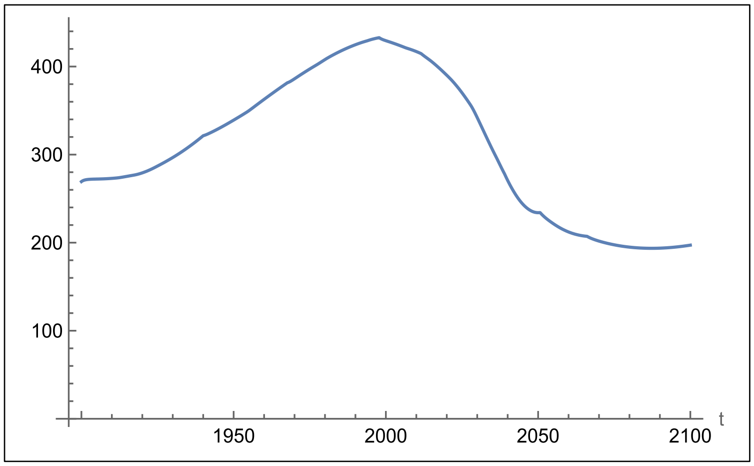

Figure **3.** World food production (in vegetable-equivalent kilograms per person-year (see Meadows et al. 1974, p. 64 for a definition of this term) by time (Year). *World3*, Benchmark Scenario 1.

1.2.2. Benchmark Scenario 2 (Meadows et al., 2004, pp. 172-174).

In this scenario, the nonrenewable resources assumed in Benchmark Scenario 1 are doubled. Benchmark Scenario 2 further postulates that advances in resource extraction technology postpone the onset of increasing extraction costs, thus allowing industry to grow 20 years longer than in Benchmark Scenario 1. But as a consequence, pollution levels rise sharply, depressing land yields and requiring massive investments in agricultural recovery. The population finally declines because of food shortages and the health effects of pollution.

1.2.3. Benchmark Scenario 3 (Meadows et al., 2004, pp. 210-214)

This scenario assumes the nonrenewable resource supply and extraction technologies assumed in Benchmark Scenario 2. It also assumes increasingly effective pollution control technology that reduces the amount of pollution generated per unit of output by up to 4 percent per year, starting in 2002. This allows much higher welfare for more people after 2040 because of fewer negative effects of pollution. But food production ultimately declines, drawing capital from the industrial sector and triggering a population collapse.

1.2.4. Benchmark Scenario 4 (Meadows et al., 2004, pp. 214-216).

This scenario adds to the pollution control technology of Benchmark Scenario 3 and a set of technologies that greatly increase the food yield per unit of land. As a consequence, agricultural activities sharply increase the land loss rate. This scenario ultimately leads to a population collapse.

1.2.5. Benchmark Scenario 5 (Meadows et al., 2004, pp. 216-218)

This scenario assumes more accessible nonrenewable resources, a better land-preservation technology than Benchmark Scenario 4, and the pollution-reducing technology of Scenario 4. This only slightly postpones the population collapse to near the end of the 21st century.

1.2.6. Benchmark Scenario 6 (Meadows et al., 2004, pp. 218-220).

This scenario assumes the world develops even more powerful pollution abatement and land protection than Benchmark Scenario 5, and further assumes conservation of nonrenewable resources. All these technologies have costs and take 20 years to be fully implemented. In combination, they yield a fairly large and prosperous population until the accumulated cost of the technologies becomes unsustainable, ending in a population collapse.

1.2.7. Benchmark Scenario 7 (Meadows et al., 2004, pp. 238-241).

This scenario assumes that after 2002 all families are limited to two children. Because of the age-structure momentum, however, the population continues to grow for another generation. The slower population growth permits industrial output to rise, until it is stopped by the cost of dealing with rising pollution (as in Benchmark Scenario 2).

1.2.8. Benchmark Scenario 8 (Meadows et al., 2004, pp. 241-244).

This scenario assumes that after 2002 families are limited to two children. The scenario sets a fixed goal for industrial output per capita. As a result, there is a "golden period" of fairly high human welfare between 2020 and 2040. But rising pollution increasingly stresses agricultural resources. Per capita food production falls, eventually degrading life expectancy.

1.2.9. Benchmark Scenario 9 (Meadows et al., 2004, 244-247).

In this scenario, population and industrial output are limited as in Benchmark Scenario 8. In addition, technologies are added to aggressively abate pollution, conserve resources, increase land yield, and protect agricultural land. As a consequence, the planet's 8 billion people enjoy a high standard of living, and the human ecological footprint continuously declines. Figure 4 shows population as a function of time in *World3* Benchmark Scenario 9. Figure 5 shows life expectancy as a function of time in Scenario 9. Figure 6 shows food produced per capita as a function of time in Benchmark Scenario 9.

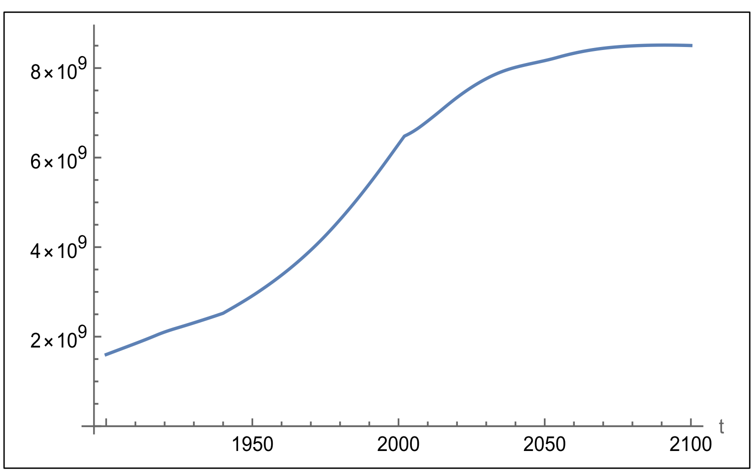

Figure **4.** World population (number of persons) vs. time (Year). *World3*, Benchmark Scenario 9.

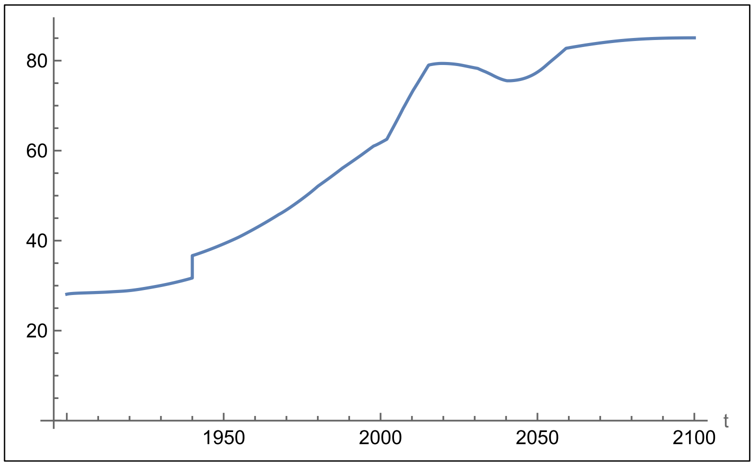

Figure 5. World average Life Expectancy (years) by time (Year). *World3*, Benchmark Scenario 9.

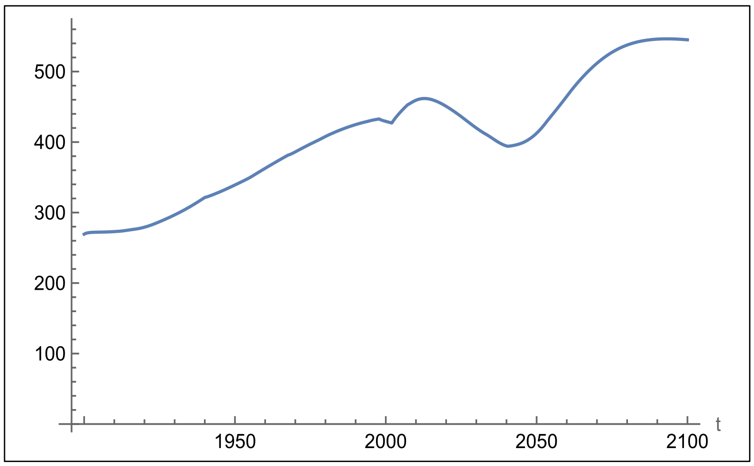

Figure **6.** World food production (in vegetable-equivalent kilograms per person-year (see Meadows et al. 1974, p. 64 for a definition), by time. *World3*, Benchmark Scenario 9.

In Benchmark Scenarios 1-8, population/resource dynamics are strongly dominated by population growth overshooting the global supply of various resources, resulting in a population peak followed by a population crash (see, for example, Figure 2). In its most rudimentary form, this behavior is the classic Malthusian catastrophe (Malthus, 1798; Ehrlich and Ehrlich, 2009) any resource required to sustain a population level must increase at least as fast as the population does, or the population will overshoot the carrying capacity of the resource and the population will collapse. In the presence of adequate resources, population tends to increase exponentially but the resources required to sustain that population increase at best linearly. Over at least the last century, for example, the global population has tended to grow at least one percent year over year (i.e., has exhibited an exponential growth rate of at least one percent per year), while agricultural output has, on average, increased at most linearly. Only Benchmark Scenario 9 avoids such a collapse.[7]

[7] The values of a few initial conditions and parameter values in the Benchmark Scenarios as described in Cellier (2019) differ slightly from those in Meadows et al. (1974). These differences are the result of a calibration of World3 that occurred between about 1975 and 2008. The differences between the predictions of the Benchmark Scenarios in Meadows et al. (1974) and the corresponding Benchmark Scenarios in Cellier (2019) that arise from the differences in the initial conditions and parameter values in Meadows et al. (1972) and Cellier (2019) are minor.

2. Method

The version (Cellier, 2019) of *World3* used in this study is Cellier (2008) hosted under the *SystemModeler* (Wolfram, 2019; Wolfram, 2022) framework. The configuration files for each of Benchmark Scenarios 1-9 used in this study are bundled with Cellier (2019). *Modelica* v3.2.2 and v3.2.3 provided the *Modelica* resources required by Cellier (2019).[8] Microsoft C++ Visual Studio provided the C++ resources required by Wolfram (2019) and Wolfram (2022). All software used in this study was executed under Windows 10 on a Dell Inspiron 545 desktop containing an Intel Q8200 quad processor clocked at 2.33 GHz and 8 GB of physical memory.

2.1. Selection of parameters to vary

Two criteria of adequacy must be satisfied in order to evaluate the sensitivity of a quantity, *Y*, to another quantity, *X*, in a given simulation/model *M*. Assume *X*' is a proxy for *X*. Then

- A1. In *M*, we vary *X* (or *X*') and observe the effect of that variation on *Y*.
- A2. The values of all independent variables and parameters in *M* other than *X* (or *X*') are kept constant.

Note that when "sensitivity analysis" is used in the sense of A1-A2, the analysis does not address whether *M* "correctly" represents the world per se. Strictly speaking, a sensitivity analysis is instead concerned with the question how, within *M*, *Y* varies with *X* (*X*').[9]

Although *World3* does not explicitly model pandemic dynamics per se, it is possible to appropriate *World3*'s parametric modeling of the effect of health services on *World3*'s variable Life Expectancy as a proxy for those pandemic effects on **Life Expectancy** that can be approximated by varying a parameter multiplier of the non-pandemic life expectancy values.

Pandemic regimes in which this kind of approximation is informative are those in which, given a specific infectious agent (e.g., a specific variant of a virus) and the time interval of interest are such that:

- At the beginning of the pandemic, the world population has no immunity to infection by the agent
- There is no significant control of the spread of the disease, and
- The fraction of the susceptible population that has been infected is small (nominally < 10%)

The beginning of the 1918 influenza pandemic satisfied (a) - (c) (Spreeuwenberg et al., 2018). The COVID-19 pandemic as of August 2022, because the dominant strain of the virus has been changing faster than fully effective control measures have been globally deployed, roughly approximates (a) – (c) (Johns Hopkins University, 2022).

More specifically, *World3* contains a parameter, **Life_Expectancy1.Lifet_Mlt_Hlth_Serv**, that models the effect of health services on **Life Expectancy**. In *World3* **Life Expectancy**, LE, is calculated as

---

[8] If Cellier (2019) is executed interactively from *SystemModeler* (Wolfram, 2019), the software used in this study produces an advisory (not an error) message stating that by default, it expects to use *Modelica* v3.2.1, but finds *Modelica* v3.2.2.. If the software used in this study is executed under *Mathematica* (Wolfram 2022), *Mathematica* produces an advisory message stating that *Modelica* v3.2.3 is used. I am not aware of any differences, for the purposes of this study, among the results produced by *Modelica* v3.2.1, v3.2.2, and v3.2.3.

[9] Following IEEE (2011), I distinguish "verification", which concerns a satisfaction relation between a software system S and its specification, from "validation", which concerns the relationship between the specification and something (naively, the "real world") that is independent of the specification and software.

LE = LN*LMF*LMHS*LMP*LMC Eq. 1

where,

LN is "Normal Life Expectancy"

LMF is "Lifetime Multiplier from Food"

LMHS is "Lifetime Multiplier from Health Services"

(called **Life_Expectancy1.Lifet_Mlt_Hlth_Serv** in Cellier (2019))

LMP is "Lifetime Multiplier from Pollution"

LMC is "Lifetime Multiplier from Crowding"

* means multiplication

Each of the multiplicands on the right-hand side of Eq. 1 is a user-settable parameter. See Meadows et al. (1974) and Cellier (2019) for definitions of the terms in Eq. 1.

The "effect of health services" are such only with respect to health contexts. Health contexts include pandemics. We would expect a pandemic satisfying (a)-(c) of Section 2.1 to reduce the effectiveness of health services that would otherwise obtain. Here I use this relationship to model the interaction of hypothetical pandemics that satisfy (a) - (c) in Section 2.1, with population/resource dynamics. In particular, I model the *effect* of such pandemics on ~200 *World3*'s variables by analyzing the sensitivity of those variables to a ±10% variation 10 in the values of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv,** for the nine World 3 Benchmark Scenarios. Note that if the values of LN, LMF, LMP, and LNC in Eq. 1 are ixed, a variation of X% in **Life_Expectancy1.Lifet_fMlt_Hlth_Serv** induces an X% variation in Life Expectancy.

The choice of ±10% bounds on the variation of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv** is broadly consistent with bounds on estimates of the global mortality rates in the 1918 influenza pandemic (Spreeuwenberg et al., 2019 (~3%)), in the bubonic plague in urban areas in the Middle Ages (Christakos et al., 2005 (~50%)), and in the COVID-19 pandemic (Johns Hopkins University, 2022 (~0.1%)).

In *World3*, **Life_Expectancy1.Lifet_Mlt_Hlth_Serv** is implemented in two tables, **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1**, and **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2**. The default values of these two tables in Benchmark Scenario 1 are shown in Figures 7 and 8.

In Benchmark Scenario 1, *World3* uses the values of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1** until the scenario time equals approximately 1940. For scenario times greater than about 1940, Benchmark 1 uses the values of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv** defined in **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.**[11]

[10] For a list of these variables, see Horner (2022).

[11] Although the switch from the values shown in Figure 8 to the values shown in Figure 9 may seem somewhat artificial, it is the result of a conscious decision by the developers of World3 to reflect the fact that health services improved rapidly in the post-WW II period (Meadows et al., 1974, pp. 75-76).

```
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1.y_vals[1] → 1}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1.y_vals[2] → 1.1}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1.y_vals[3] → 1.4}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1.y_vals[4] → 1.6}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1.y_vals[5] → 1.7}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1.y_vals[6] → 1.8}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1.y_vals[7] → 1.8}
```

Figure 7. Default values of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_1**. Benchmark Scenario 1 uses these values of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv** prior to Scenario Year 1940.

```
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[1] → 1}
Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[2] → 1.5}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[3] → 1.9}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[4] → 2}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[5] → 2}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[6] → 2}
{Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[7] → 2}
```

Figure 8. Default values of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2**. Benchmark Scenario 1 uses these values of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv** at or later than Scenario Year 1940.

To summarize, by varying the (i.e., Benchmark Scenario-) values of parameter **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2** by ±10%, we can approximate the effect, on ~200 *World3* variables, of a pandemic that satisfies the constraints identified in (a)-(c) of Section 2.1.[12]

Accordingly, in this study, the *SystemModeler/Mathematica* (Wolfram, 2019; Wolfram 2022) functions **SystemModelSimulateSensitivity** and **SystemModelPlot** were used to compute the sensitivity of ~200 World3 variables to ±10% variation in **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals** for Benchmark Scenarios 1-9 on the platform described in Section 2.0. See Horner (2022) for further detail.

3. Results

The sensitivity source code and results described in Section 2.0 were saved to a PDF file, available at Horner (2022). The collective wall-clock time for these calculations on the platform described in Section 2.0 was approximately 3 hours.

[12] See Section 4 for discussion of tradeoffs among various approaches to modeling pandemics "within" the World3 framework.

Compared to the sensitivity of the World3 variables in Benchmark Scenarios 1-8 to variation in **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2**, the corresponding variables in Benchmark Scenario 9 exhibit distinctive stability in the presence of variation in **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2**. Figures 9-14 illustrate this stability by comparing the sensitivity of three *World3* variables (**Life_Expectancy1.Eff_Hlth_Serv_PC.Smooth_of_Input.Integrator1.y**, **Food_Production1.Agr_Inp.Integrator1.y**, and **Labor_Utilization1.Labor_Util_Fr_Del.Integrator1.y**, respectively) to **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2** in Benchmark Scenarios 1 and 9. In each of Figures 9-14, the green curve corresponds to a +10% increase in the default value of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2[1]**. The blue curve corresponds to the default value of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2[1]**. The orange curve corresponds to a 10% decrease in the nominal value of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2[1]**.

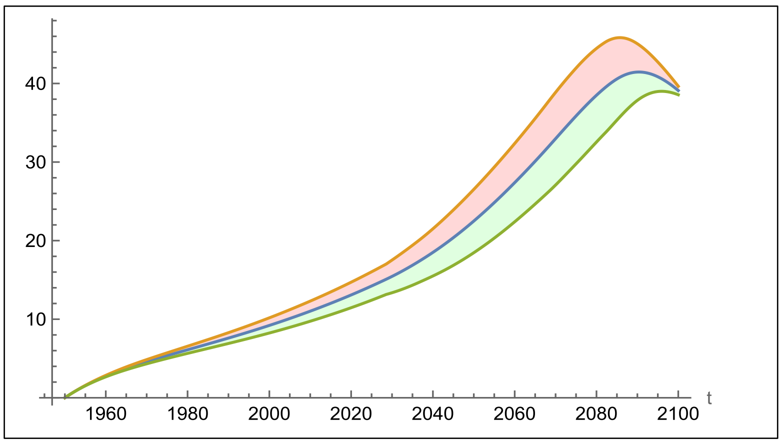

Figure 9. Sensitivity of **Life_Expectancy1.Eff_Hlth_Serv_PC.Smooth_of_Input.Integrator1.y** to **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[1]** in Benchmark Scenario 1.

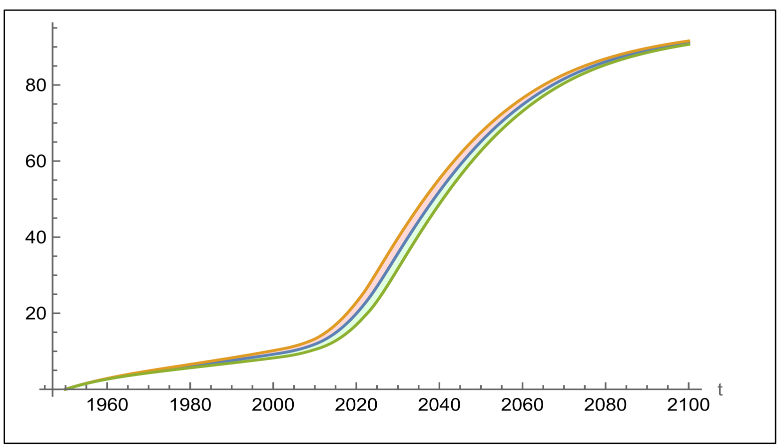

Figure 10. Sensitivity of **Life_Expectancy1.Eff_Hlth_Serv_PC.Smooth_of_Input.Integrator1.y** to **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[1]** in Benchmark Scenario 9.

The results shown in Figures 9-14, together with Horner (2022), suggest that the population/resource-management policies and practices of *World3*'s Benchmark Scenario 9 can strongly mitigate the fiscal and physical disruption of a pandemic satisfying (a)-(c) of Section 2.1.

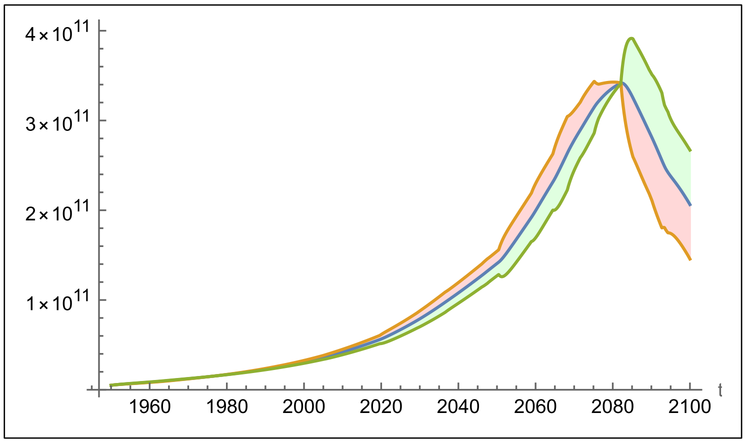

Figure 11. Sensitivity of **Life_Expectancy1.Eff_Hlth_Serv_PC.Smooth_of_Input.Integrator1.y** to **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[1]** in Benchmark Scenario 1.

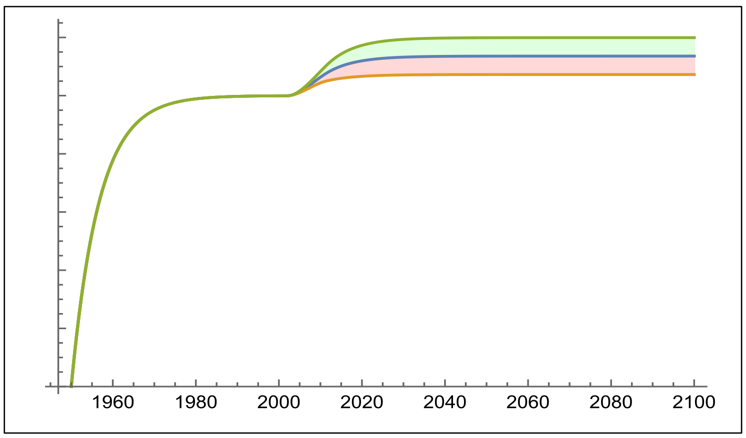

Figure 12. Sensitivity of **Life_Expectancy1.Eff_Hlth_Serv_PC.Smooth_of_Input.Integrator1.y** to **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[1]** in Benchmark Scenario 9.

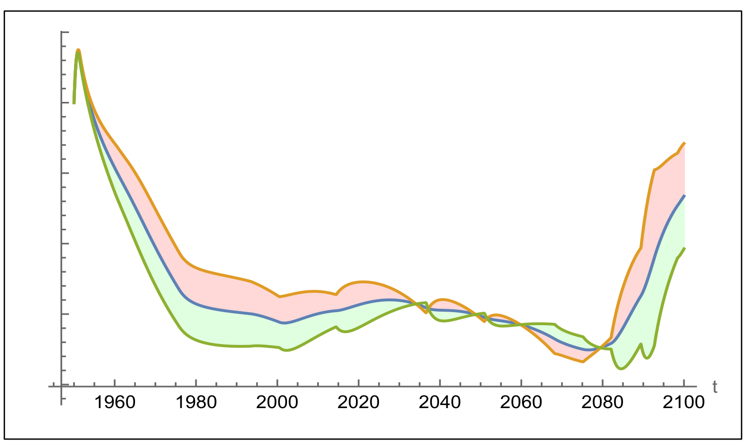

Figure 13. Sensitivity of **Life_Expectancy1.Eff_Hlth_Serv_PC.Smooth_of_Input.Integrator1.y** to **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[1]** in Benchmark Scenario 1.

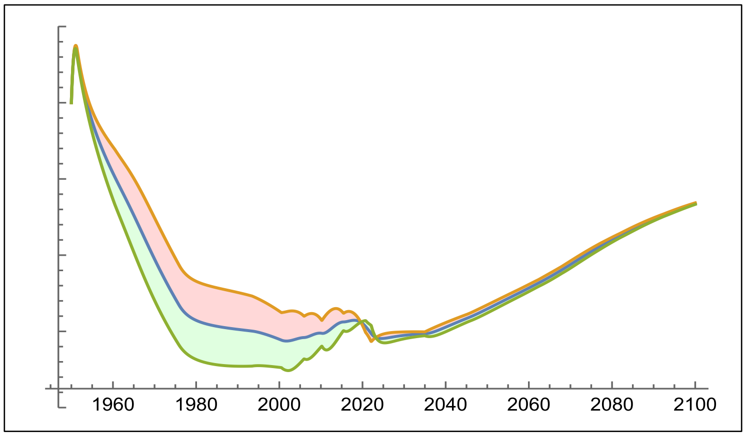

Figure 14. Sensitivity of **Life_Expectancy1.Eff_Hlth_Serv_PC.Smooth_of_Input.Integrator1.y** to **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2.y_vals[1]** in Benchmark Scenario 9.

4. Discussion

The results of the study motivate several observations.

1) Using *World3* to help probe the interaction of human population dynamics and pandemic dynamics is not a panacea: the effects of pandemics on population/resource dynamics might lie outside what *World3* per se can plausibly represent.13 If so, using *World3* to help bound estimates of the interaction of pandemic, and human population/resource, dynamics could cause us to seriously mis-estimate that interaction.

   Though well taken, it should be noted that this kind of concern is not unique to *World3*, or even to simulation-based estimation in general: it applies to *all* ampliative (non-deductive) inferences (Salmon, 1967, 8-12) that have not been, or for various pragmatic reasons (e.g., ethical, financial, technological) cannot be, tested. Ampliative inference lies at the heart of all empirical science (Hume, 1739, Book I, Part III; Salmon, 1967; Symons et al., 2012; Winsberg, 2010; Symons and Alvarado, 2019).

2) It has been argued by several *World3* critics that technological changes could render *World3*'s sobering predictions moot. Increases in agricultural productivity, one variant of that argument goes, could solve the predicted food shortage problem. (See, for example, Simon, 1996, esp. Chap. 6). Let's call the class of arguments that assert that technological changes could render *World3*'s predictions moot, "technological change" arguments.

   This class of arguments, though seemingly plausible, is deeply problematic. It is simply not true that the *World3* Benchmark Scenarios do not consider technological change. Each of Benchmark Scenarios 2-9 implicitly hypothesize technological changes (including increased food productivity in particular) with respect to Benchmark Scenario 1 (BAU). Benchmark Scenario 9, moreover, outlines the scope of a set of technological changes that could prevent the population-collapse problem.

[13] Cellier (2019) implements range-of-value controls on ~100 variables, mainly to ensure that the numerical integration functions in *World3* operate within acceptable error limits. Some of these range-of-value controls coincidentally happen to abort scenarios that have parameter values that lie outside regions for which *World3* has not been calibrated.

Some "technological change" arguments do not specify which technological changes would render *World3*'s predictions moot. Such formulations are not testable even in principle, raising the question of whether those formulations are even part of empirical science. (For a discussion of this class of problems, see: Hempel, 1965, pp. 3-4 and Quine, 1961, esp. Section 6).

3) Models that integrate the interaction of population/resource-, with pandemic-, dynamics are inherently high-dimensional, and as a consequence using them might seem to entrain intractable calibration problems. Though this concern is not to be taken lightly, the Central Limit Theorem (Chung, 2001, esp. Chap. 7) ensures that Monte Carlo estimates of dynamics (Liu, 2001) converge. ("Convergence" in this sense is a necessary, but not a sufficient, condition for "convergence to 'real-world' scenarios".) We could, in particular, use *World3* as the ensemble-generator in a Monte Carlo simulation. (A Monte Carlo approach of this kind would require at least tera-scale computing resources.)

4) Maximum entropy techniques (Jaynes, 1988; Kapur and Kesavan, 1992; Cover and Thomas, 1991, esp. Chap. 12; Newman, 2010, esp. Chap. 15) could be used to estimate expected values of *World3* metrics.

5) One could explicitly add a compartmental epidemiological model such as SEIRD to the baseline *World3* code. Implementing modifications to the *World3* code, however, would require introducing additional independent parameters or variables. There are tradeoffs between introducing those complexities on the one hand vs. appropriating -- where possible -- the semantics of **Life_Expectancy1.Lifet_Mlt_Hlth_Serv_2**. It could be argued, for example, that re-purposing the indicated parameters "overloads" the default intended semantics of those parameters. ("Intended semantics" in this sense is not determined by software and hardware per se, but by a relationship between software and hardware on the one hand, and intentions implied by the system specification on the other hand (Turner, 2011). All other considerations being the same, semantic overloading of program elements can increase software and conceptual complexity and thereby increase the risk of programming or usage errors. (See, for example: Ullman, 1988, esp. Chap. 7; Aho et al., 1983, esp. Section 1.6; Booch and Bryan, 1993; and Parnas, 1972). Against this, it can be argued that at least some kinds of semantic overloading allow us to aggregate similar items better than alternative approaches; indeed, some modern programming languages (ISO/IEC, 2017; MITRE Corporation, 2000) have fundamental syntactic and semantic resources to regiment such overloading.

   Not least, adding new variables or parameters to *World3* would introduce variant versions of the *World3* software, and thus would increase the complexity of World3's configuration management and calibration spaces (Leon, 2015). Changing the values of parameters in a software system, of course, introduces data-configuration management issues in its own right (Symons and Alvarado, 2016).

   In short, any approach to the problem of extending a given simulator involves tradeoffs.

6) A parameter-variation technique analogous to the one used in this study could be used to analyze the effect of CO_2-induced temperature increases on agricultural production. More specifically, although *World3* does not explicitly model greenhouse-gas (GHG) effects directly, it does parametrically model the effect of "persistent pollution" on agricultural production in a way that appears to be amenable to the variation of parameters method used in the present study. Future work will pursue this claim.

Acknowledgement

This work benefited from discussions with Toufiq Siddiqi, Jorge Soberón, John Symons, Ramón Alvarado, Anthony Pawlicki, Richard Stutzke, and Richard Frank. Not least, the paper benefited greatly from recommendations from two anonymous reviewers. For any infelicities that remain, I am solely responsible.

References

Aho, A.V., Hopcroft, J.E. and Ullman, J.D. (1983), *Data Structures and Algorithms*, Addison-Wesley, Publishing Co., Reading, MA.

Apostol, T. M. (1967), *Calculus*, Vol. I, 2nd ed., John Wiley & Sons, Inc, New York, NY.

Boehm, B.W. (1981), *Software Engineering Economics*, Prentice-Hall, Englewood Cliffs, NJ.

Boehm, B.W., Abts, C., Brown, A.W., Chulani, S., Clark, B.K., Horowitz, E., Madachy, R., Reifer, D. and Steece, B. (2000), *Software Cost Estimation with COCOMO II*, Prentice-Hall, Englewood Cliffs, NJ.

Booch, G. and Bryan, D. (1993), *Software Engineering with Ada,* 3rd ed., Addison-Wesley Publishing Co., Reading, MA.

Cellier, F.E. (2008), "*World3* in Modelica: creating system dynamics models in the Modelica framework", available at: https://inf.ethz.ch/personal/cellier/Pubs/World/modelica_08_World3.pdf (accessed 28 April 2019).

Cellier, F.E. (2019), "SystemDynamics.WorldDynamics.World3", available at: https://build.openmodelica.org/Documentation/SystemDynamics.WorldDynamics.World3.html (accessed 17 March 2019).

Chung, K.L. (2001), *A Course in Probability Theory*, 3rd ed., Academic Press, San Diego, CA.

Cole, H.S.D., Freeman, C., Jahoda, M. and Pavitt, K.L.R. (Ed.s) (1973), *Models of Doom: A Critique of the Limits to Growth*, Universe Publishing, New York, NY.

Christakos, G., Olea, R.A., Serre, M.L., Wang, L.L. and Yu, H.L. (2005), *Interdisciplinary Public Health Reasoning and Epidemic Modelling: the Case of Black Death*. Springer, New York, NY.

Cover, T.M. and Thomas, J.A. (1991), *Elements of Information Theory*, John Wiley, New York, NY.

Ehrlich, P.R. and Ehrlich, A.H. (2009), "The population bomb revisited", *Electronic Journal of Sustainable Development*, Vol. 1, pp. 163‐171.

Hempel, C.G. (1965), "Studies in the logic of confirmation", in: Hempel C.G., *Aspects of Scientific Explanation and Other Essays in the Philosophy of Science*, The Free Press, New York, NY, pp. 3-51.

Herrington, G. (2020), "Update to limits to growth: comparing the World3 model with empirical data", *Journal of Industrial Ecology*, Vol. 25, pp. 614‐626.

Horner, J.K. (2022), "Supplemental Information for "A World3 analysis of the sensitivity of population/resource dynamics to pandemic-scale variation in life expectancy", available at: https://doi.org/10.7910/DVN/0KVMNE, Harvard Dataverse, V1.

Hume, D. (1739), *A Treatise of Human Nature*, ed. by L.A. Selby-Bigge, Oxford University Press, Oxford, England.

IEEE (2011), *P1490/D1, May 2011 - IEEE Draft Guide: Adoption of the Project Management Institute (PMI) Standard: A Guide to the Project Management Body of Knowledge (PMBOK Guide ‐ 2008)*, 4th ed., IEEE, available at: https://reference.globalspec.com/standard/3795974/p1490-d1-may-2011 (accessed 5 December 2022).

ISO/IEC (2017), 14882:2017, *Programming Languages* -- C++, available at: https://www.iso.org/standard /79358.html (accessed 5 December 2022).

Jaynes, E. T. (1988), "The relation of Bayesian and maximum entropy methods", in: Erickson, G.J. and Smith C.R. (Ed.s), *Maximum-entropy and Bayesian Methods in Science and Engineering*, Vol. 1, Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 25-29.

Johns Hopkins University Center for Systems Science and Engineering (CSSE) (5 August 2022), COVID-19 Data Repository available at: https://github.com/CSSEGISandData/COVID-19 (accessed 5 August 2022).

Kapur, J.N. and Kesavan, H.K. (1992), *Entropy Optimization Principles with Applications*, Academic Press, San Diego, CA.

Keyfitz, N. (1971), "Changes of birth and death rates and their demographic effects", in: *Rapid Population Growth*, Johns Hopkins University Press for the National Academy of Sciences, Baltimore, MD.

Leon, A. (2015), *Software Configuration Management Handbook*, Artech House Publishers, London, England.

Liu, J. S. (2001), *Monte Carlo Strategies in Scientific Computing*, Springer, New York, NY.

Malthus, T.R. (1798), *An Essay on the Principle of Population*, J. Johnson, London England.

Meadows, D.H., Meadows, D.L., Randers, J. and Behrens, W.W. (III) (1972), *The Limits to Growth*, 2nd ed., The New American Library: New York, NY.

Meadows, D.H., Randers, J. and Meadows, D.L. (2004), *The Limits to Growth: The 30-Year Update*. Chelsea Green, White River Junction, VT.

Meadows, D. L., Behrens, W.W. III, Meadows, D.H., Naill, R.F., Randers, J. and Zahn, E.K.O. (1974), *Dynamics of Growth in a Finite World*, Wright-Allen Press, Cambridge, MA.

MITRE Corporation (2000), *Ada Reference Manual*. ISO/IEC 8652:1995(E) with COR.1:2000.

Newman, M.E.J. (2010), *Networks: An Introduction*, Oxford University Press, Oxford, England.

Nørgård, J.S., Peet, J. and Ragnarsdóttir, K.V. (2010), "The history of the Limits to Growth", *The Solutions Journal*, Vol. 1 No. 2, pp. 59-63.

Open Modelica Organization (2019), *Open Modelica*, available at: https://www.openmodelica.org/ (accessed 28 April 2019).

Parnas, D.L. (1972), "On the criteria to be used in decomposing systems into modules", *Communications of the ACM*, Vol. 15 No. 12, pp. 1053‐1058.

Pugh, A.L. (1963), *DYNAMO User's Manual*, The MIT Press, Cambridge, MA.

Quine, W.V.O. (1961), "Two dogmas of empiricism", in: Quine, W.V.O., *From a Logical Point of View*, Harper and Row, New York, NY, pp. 20-46.

Randers, J. (2012), *2052: A Global Forecast for the Next Forty Years*, Chelsea Green, White River Junction, VT.

Richmond, B. (2013), *An Introduction to Systems Thinking*, STELLA, ISEE Systems, Lebanon, NH.

Roser, M. and Ritchie H. (2022), *Our World in Data: Food Supply*, accessible at: https://ourworldindata.org /food-supply (accessed 1 September 2022).

Rumbaugh, J., Jacobson, I. and Booch, G. (1999), *The Unified Modeling Language Reference Manual*, Addison Wesley, Reading, MA.

Salmon, W.C. (1967), *The Foundations of Scientific Inference*, University of Pittsburgh Press, Pittsburgh, PA.

Schlaer, S. and Mellor, S.J. (1992), *Object Lifecycles: Modeling the World in States*, Yourdon Press, New York, NY.

Simon, J.L. and Kahn, H. (1984), *The Resourceful Earth*, Basil Blackwell, Inc., New York, NY.

Simon, J.L. (1996), *The Ultimate Resource 2*, Princeton University Press, Princeton, NJ.

Smith, B.C. (1996), *On the Origin of Objects*, The MIT Press, Cambridge, MA.

Spreeuwenberg, P., Kroneman, M. and Paget J. (2018), "Reassessing the global mortality burden of the 1918 influenza pandemic", *American Journal of Epidemiology*, Vol. 187, pp. 2561-1267.

Symons, J.F. and Alvarado, R. (2016). "Can we trust Big Data? Applying philosophy of science to software", *Big Data and Society 3*, available at: https://doi.org/10.1177/2053951716664747 (accessed 5 December 2022).

Symons, J.F. and Alvarado, R. (2019), "Epistemic entitlements and the practice of computer simulation", *Minds and Machines*, Vol. 29, pp. 37-60.

Symons, J.F., Boschetti, F., Fulton, E.A. and Bradbury, R.H. (2012), "What is a model, why people don't trust them and why they should", in: *Negotiating Our Future: Living scenarios for Australia to 2050*, Vol. 2, Australian Academy of Science, pp. 107-119.

The Modelica Association (2019), *Modelica*, available at: https://www.modelica.org/ (accessed 28 April 2019).

Turner, G.M. (2008), "A comparison of The Limits to Growth with 30 years of reality", *Global Environmental Change*, Vol. 18, pp. 397-411.

Turner, G.M. (2014), "Is global collapse imminent?", MSSI Research Paper No. 4, Melbourne Sustainable Society Institute, available at: https://sustainable.unimelb.edu.au/__data/assets/pdf_file/0005/2763500/MSSI-ResearchPaper-4_Turner_2014.pdf (accessed 13 August 2019).

Turner, R. (2011), "Specification", *Minds and Machines*, Vol. 21 No. 2, pp. 135‑152.

Ullman, J.D. (1988), *Principles of Database and Knowledge-Base Systems*, Volume I, Computer Science Press, Rockville, MD.

United Nations, Department of Economic and Social Affairs, Population Division (2019), *World Population Prospects: The 2019 Revision*, available at: https://www.un.org/development/desa/pd/news/world-population-prospects-2019-0 (accessed 10 August 2022).

Voit, E.O. (2000), *Computational Analysis of Biochemical Systems*. Cambridge University Press, Cambridge, England.

Vynnycky, E. and White, R.G. (eds.) (2010), *An Introduction to Infectious Disease Modelling*, Oxford University Press, Oxford, England.

Winsberg, E. (2010), *Science in the Age of Computer Simulation*, University of Chicago Press, Chicago, IL.

Wolfram Research (2019), *System Modeler v12.0*, available at: https://www.wolfram.com/SystemModeler/ (accessed 24 March 2019).

Wolfram Research (2022), *Mathematica v13.1 Home Edition*, available at: https://www.wolfram.com/mathematica-home-edition/ (accessed 15 March 2022).