European Journal of Sustainable Development Research
2024, 8(4), em0274
e-ISSN: 2542-4742
https://www.ejosdr.com/

MODESTUM

Research Article

OPEN ACCESS

Addressing sustainability: Modelling to enhance participation as a global citizen

Peter L. Galbraith [1]*, Diana M. Fisher [2]

[1] School of Education, University of Queensland, Brisbane, QLD, AUSTRALIA
[2] Affiliate Factulty in the Complex Systems Program, Portland State University, Portland, OR, USA
*Corresponding Author: p.galbraith@uq.edu.au

Citation: Galbraith, P. L., & Fisher, D. M. (2024). Addressing sustainability: Modelling to enhance participation as a global citizen. *European Journal of Sustainable Development Research, 8*(4), em0274. https://doi.org/10.29333/ejosdr/15675

ARTICLE INFO

Received: 21 May 2024

Accepted: 21 Sep. 2024

ABSTRACT

The term "wicked problem" has been coined to describe real-world problems that feature non-linearity and simultaneity among model equations, making simulation the only approach to solution. Such was the 2019 problem set by the international mathematical modelling challenge. This problem involved estimating the carrying capacity of earth, and no student team from any country was successful. The paper addresses *sustainability* issues within the problem through a modelling approach that can be completed successfully using recently available free on-line software. The software is designed to be equally accessible to modelling professionals, and students from senior high school and beyond. A purpose is to introduce and apply a methodology by providing detail sufficient for interested readers to engage with the thinking, re-create the model, and gain expertise with the approach if that is their wish. It finally provides examples of other 'wicked' problems that have been addressed successfully by secondary students.

Keywords: carrying capacity, system dynamics, simulation, Stella, wicked problems

INTRODUCTION

Concern about the sustainability of planet earth looms large in the consciousness of all, not least among those who have inherited the environment and challenges of today's world. Since skills to assess identified challenges and rationally seek solutions to emerging problems on a national and global scale are needed in unprecedented ways, such needs devolve increasingly on the ability of education systems to deliver the necessary training. National education statements have flagged ideals for mathematics to provide students with applicable skills for the workplace, for use as responsible citizens, and to enhance decision making in their personal lives (e.g., Australian Curriculum Assessment and Reporting Authority [ACARA], 2017; National Governors Association, 2010; OECD, 2021). An espoused goal is to develop learning to include the independent solving of problems in the world outside the classroom, through the development of abilities that will endure throughout life.

Such ideals have also formed a motivating force behind the development of the international mathematical modeling challenge (IM^{2}C) (see IM^{2}C, 2024). As noted on its website the challenge

> is based on the firm belief that students and teachers need to experience the power of mathematics to help better understand, analyze and solve real world problems outside of mathematics itself–and to do so in realistic contexts. The challenge is launched in the spirit of promoting educational change.

One stimulus for this present paper was the 2019 IM^{2}C problem whose essence is provided by the following:

> Use mathematical modelling to determine the current carrying capacity of the earth for human life under today's conditions and technology. What can the human population realistically do to raise the carrying capacity of the earth for human life in perceived or anticipated future conditions?

That the problem proved beyond the capabilities of every participating international team was confirmed by comments from Garfunkel et al. (2021). They noted that a common approach was to consider each limiting factor individually and determine the carrying capacity based on the factor whose resource base ran out first. Consequently, the teams did not consider that different critical resources are not independent. This outcome is not surprising, given that the enactment of a successful modelling process requires that students possess mathematical resources sufficient to develop a model complex enough to address the question posed. Here, the presence of non-linearity and simultaneity within model equations creates demands that only simulation methods can deal with.

Common CAS packages do not provide the necessary specifics, and in the absence of appropriate software this need cannot be provided for within educational programs, including advanced ones. So it proved.

The above is an example of so-called "wicked problems" that increasingly confront global decision makers. Problems presented by spreading pandemics, economic recessions, environmental degradation, impacts of global warming, re-settling of homeless people and so on involve complex systems, and require analysis defined by attention to interconnections, feedback, non-linearity, and delays. For such problems key variables are not necessarily obvious up front, requiring that they be created rather than identified, and where their definitions and the relationships driving their growth and decline are challenges a modeller must engage with. This frequently involves interdisciplinary understanding and involvement.

This paper sets out to demonstrate how a category of problems, increasingly significant in the modern world, and unable to be addressed using conventional mathematical methods, can be made accessible, not only to professionals new to the methodology, but to secondary school, college, and university students–including, importantly, those aspiring to become mathematics teachers.

It aims both to provide specific experience with a methodology geared to the needs of a "wicked" sustainability problem, and to indicate how its wider application might be employed. This approach is distinct from discussions in the literature which do not address interdependence in an analytical manner. Such contributions are important within the field as a whole but are not centrally relevant here.

Following the introductory sections the paper can be read at three levels. First, we will provide an overview of what system dynamics (SD) modelling can achieve in terms of the problem at hand. If the content of these sections is accessed, deeper levels of detail are facilitated.

At the second level, model mathematization is provided by reading the text in each section up to but not including the boxed material. At the third level the boxed material additionally provides input which enables interested readers to reproduce the model. At this third level the Stella model is fully formulated by entering the boxed material provided into the dialogue boxes revealed by clicking on the respective icons.

MODELLING IN COMPLEX SYSTEMS THROUGH SYSTEM DYNAMICS

SD was invented by Forrester (1969) at Massachusetts Institute of Technology in the middle of last century, to address problems that feature non- linearity and simultaneity, characteristics that require simulation as an approach to solution. It addresses the need to create variables of relevance and build equations relating them before an approach to their solution through simulation can be undertaken. While the development in 1985 of Stella, followed shortly after by parallel software (Powersim and Vensim), provided visual, icon-based approaches as an effective problem-solving agent, software costs restricted such modelling to industrial and professional applications supported by substantial funding. Recently the provision of a free on-line version of Stella software (Isee Systems, 2024) has brought the fundamentals of SD modelling within the reach of all with internet access, including secondary school students.

In pursuing the purpose indicated in the background the following material has been developed with three intentions in mind.

(a) The construction of a SD model to illustrate an approach to the 2019 IM^{2}C carrying capacity problem. The intention is to provide detail sufficient for the developed model to be reconstructed and run by any reader interested in acquiring capacity with the methodology. Only reasonable facility with algebra is required–necessary calculus concepts are inbuilt through the software.

(b) To construct the model within the resource limits of the free, web-based SD modelling software that is accessible to all with internet access.

(c) To provide examples illustrating successful use of SD methodology and the software by secondary school students.

Estimates of the future carrying capacity of earth (e.g., by the UN) seem to have based projections exclusively on assumed future fertility values (children born per female lifetime). While increasing global temperatures have been flagged as a major matter of concern, this does not seem to have been allowed to influence the projections. The approach here allows world population, industrial development, and global temperature to mutually influence each other. A purpose of the approach is to provide agency, such that consumers are equipped to test assertions, rather than being asked to accept claims representing individually favored positions.

This represents one of the innovative contributions of the approach in this paper, which while illustrated through a carrying capacity problem, enables access to other problems featuring interdependencies. We consistently hear expressions like "the science is in" presented on behalf of both sides of contested issues such as global warming, and where neither side is prepared to concede to the arguments of the other. SD provides a medium within which protagonists of opposing views can be brought to the same table to have views tested. A model (or models) is constructed to contain the influences that interested parties claim are centrally involved, adapted and modified as they would wish. When this is agreed, and the model run, the simulation outcome represents the impact of these agreed influences in combination. It is more difficult to cling to subjective expectations and untested claims when they are exposed through testing in a public domain.

Model Development Characteristics

In terms of the commonly represented modelling cycle summarized in **Figure 1** (e.g., Galbraith, 2024), SD modelling follows the same overall structure, with some special features that are a consequence of its essential characteristics.

1. Specify the modelling task in terms of its real-world context →2. Formulate a mathematical model →3. Solve the mathematics in the model → 4. Interpret outcomes in terms of their contextual meanings → 5. Validate/evaluate outcomes in terms of the real context → 6. Revisit the solution process as necessary–and when satisfactory document and report outcomes.

Figure 1. Basic modelling cycle (e.g., Galbraith, 2024)

Specifically, these involve articulated rounds of formulation, solution (simulation), interpretation and evaluation. In SD, formulation is more structured (by feedback processes) than is typical for modelling in general. As a consequence, sensitivity testing serves an essential purpose within formulation by systematically testing mathematical properties of an emerging model across a range of parameter values. (In conventional modelling sensitivity testing is typically used for evaluation to test the robustness of a proposed solution in terms of its real-world usefulness. This happens as well.)

Output from SD models is obtained in the form of behavior modes exhibited by variables of interest, not in terms of point predictions. For example, persistent wave like behavior tells a useful story when the accurate pinpointing of peaks and troughs is not possible due to imprecision or absence of data. Different policies can be tested for effectiveness in avoiding calamities, and for improving or changing existing behavior. This is achieved through changing parameter values, and/or by amending model structure. The following section introduces and illustrates the model building properties of *Stella* [1] software–for those without prior experience of its purpose and action.

Model Building With Stella

Four icons are used to create SD models. We use simple illustrations to indicate how these work in terms of familiar mathematics, and then in the model how they are used to build non-linear structures, essential for complex systems problems.

A *stock* (**Figure 2**) depicts a main function whose behavior we want to track over time. It is an accumulator, an integral. Examples include tangible quantities such as population, food, temperature, sick people, number of machines; but also intangible quantities that can wax and wane such as morale, motivation, depression and so on. At any moment in time a stock will contain a particular amount of content.

A *flow* represents the rate at which the stock value changes. A flow with the arrowhead pointing toward (away from) the stock means that it respectively increases (decreases) the stock value. (Mathematically the collection of flows for one stock represents the first derivative of that stock.) If the stock is population, an inflow would be births per year, and an outflow would be deaths per year, as in the illustration below. *Converters* hold parameters or simple formulas or graphical definitions. In the example below the population stock (persons) has an inflow (births) and an outflow (deaths) measured in persons/year. Respective *converters* contain the

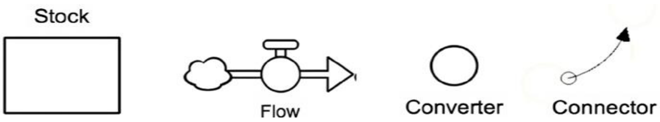

Figure 2. The four icons used to create an SD model (Fisher, 2018)

birth_fraction (fraction of population giving birth each year), and death_fraction (fraction of population dying in the same year). *Connectors* send information from one model component to another, and visually designate dependencies of one model component on another. The simulation time unit (DT) is a fractional interval[2] of the model time unit. It is used for updating model values using the chosen numerical integration method (e.g., Euler). The simulation duration is specified by the modeller e.g., 200 years with a start time of 1950. The program uses recursive numerical calculations to update model values, recalculating at each time step (DT). If the model time unit is 1-year, then setting DT = 0.25 means that model values are updated every 3 months.

The model workspace is obtained by clicking the following link: https://www.iseesystems.com/store/products/stella-online.aspx and selecting the free online version.

The model in part a in **Figure 3** is then created by clicking, dragging, connecting, and labelling the component icons using the Stella workspace where they appear as menu choices across the top of the page. For this illustration birth fraction (0.035) and death fraction (0.02) are held fixed throughout the simulation for an initial population of 3,000,000,000.

Clicking on the respective icons opens dialogue boxes–in which, for this example, the modeller inserts 8 entries identified as (a) to (h) in **Figure 4**.

The start time (1950), the simulation time (200 years), and the timestep choice (here DT = 1) are entered in the Model Settings box by the modeller. The software inserts the #step and calculates the values of all variables at successive timesteps## (See # and ## in **Figure 4**). For example:

First calculation: births (1) = 105,000 persons/year; deaths (1) = 60,000 persons/year

Population (1) = 3,000,000,000 +105,000,000 – 60,000,000 = 3,045,000,000 {persons}etc.

Mathematically the equation simulated is $dP/dt = 0.015P$, with $P(0) = 3,000,000,000$. The software generated graph (using numerical integration) is shown in part b in **Figure 3**. (The numerical output approximates the familiar analytical result $P = 3,000,000,000e^{0.015t}$).

[1] iseesystems.com

[2] The DT of the simulation software is like the 'dt' of a calculus integral, or more accurately like a Riemann sum or Simpson's rule approximation of a calculus integral.

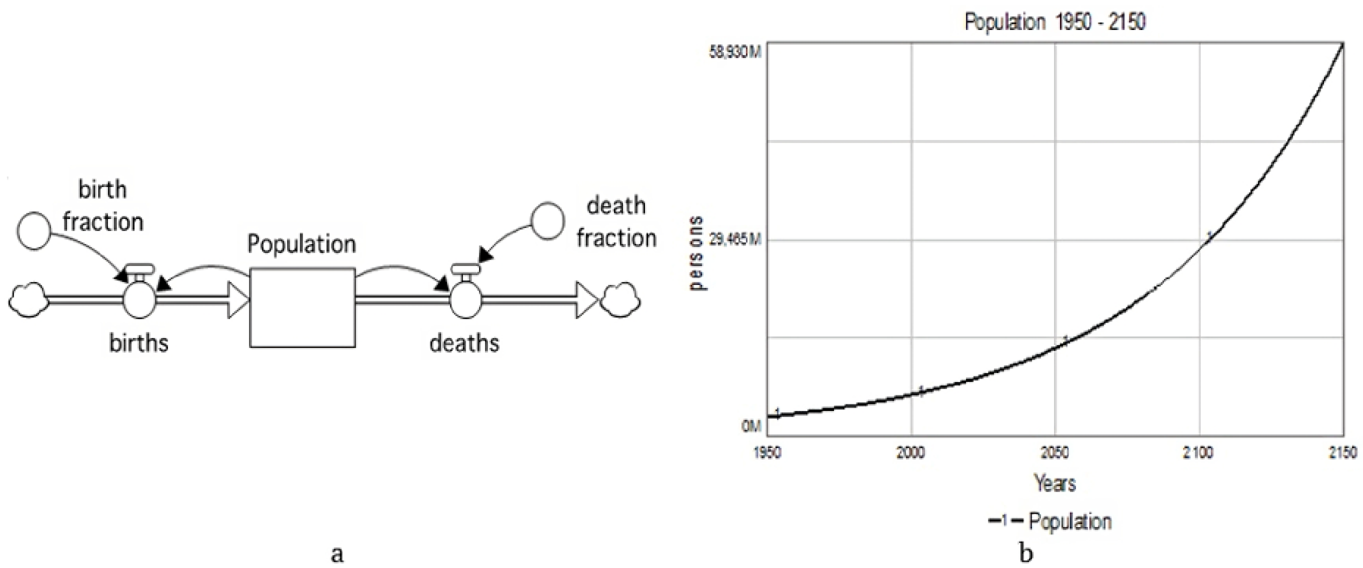

Figure 3. A simple population model: (a) Diagram & (b) Output (Source: Authors' own elaboration)

(a) Population = 3000000000 (Sets initial population): (b) Units = persons
(c) birth fraction = 0.035 (d) Units=years^-1: (e) death fraction= .02 (f) Units=years^-1
(g) births=Population*birth fraction: (h) deaths=Population*death fraction
#Population(t) = Population(t - dt) + (births - deaths) * dt, INIT Population = 3,000,000,000
##Integration is performed by the software which generates numerical output updated at each time step.

Figure 4. Entries (Source: Authors' own elaboration)

Note regarding the meaning of the term "rate". In SD rates are flows which augment or deplete stocks, so are measured in persons/year or similar units. As part of everyday living we may hear that interest rates are to be raised or lowered. This refers, for example, to the fraction of a dollar that each invested dollar will earn during a prescribed period (e.g., 3% per annum). The unit is year^{-1}, as is the case for the respective birth and death fractions here.

For those interested additional examples of simple introductory models are available at https://exchange.iseesystems.com/.

DEVELOPING A CARRYING CAPACITY MODEL

The limits to growth study (Meadows et al., 1972) and later follow up studies, investigated the potential impact of increasing population on interacting and depleting resource bases such as food production, land availability, industrialization, and non-renewable resources. Its carefully qualified projections generated considerable controversy, including misinterpretations that seemed at times mischievous. The comments of Garfunkel et al. (2021) suggest that a similar approach may have been anticipated for the IM^{2}C problem. But as observed, participants were unable to make progress in the manner expected.

Our approach here is different and has been motivated by two main considerations. Firstly to take account of increasing concerns about global warming that have been impacting on people of all ages, including school children. Secondly, to create a model that is accessible using the free version of Stella software (Stella Online), with its limit on the number of variables (3 stocks within a total of 20 variables) that can be included.

In contrast with approaches that focus on the depletion of inter-dependent resources our approach considers what may occur if increasing temperatures impact on global activity and human welfare before resource shortages as such begin to bite. The approach explores possibilities generated by "if-then" scenarios and does not set out to predict a particular future.

Situating the Model

The carrying capacity for any species is the maximum number of individuals that can be indefinitely supported at a given consumption level by a given environment, and for humans world estimates differ substantially. One meta study (taking all available studies into account), inferred lower and upper bounds for estimates to be 0.65 billion and 98 billion people, respectively. Such a range is not overly helpful!

United Nations (UN) projections (**Figure 5**) of future world population are available on *ourworldindata.org*. Three main scenarios have been developed for predicting world population numbers in 2100 based on different assumptions about average world fertility levels (children born per female lifetime). These are high variant (14.8 billion); medium variant (10.4 billion); and low variant (7 billion). The most likely of these is deemed to be the medium variant, which is based on a continuing decreasing trend in fertility levels to around 1.94 in 2100–below the replacement level of 2.1. The high and low variants simply assume that worldwide fertility rates are respectively a given amount higher and lower than this figure. A fourth alternative (19.1 billion)–the constant fertility case - is deemed to be unrealistic as it assumes that fertility rates maintain their present, more elevated level of about 2.4. Assumptions about future fertility levels seem to be largely speculative, as different organizations vary in their respective estimates.

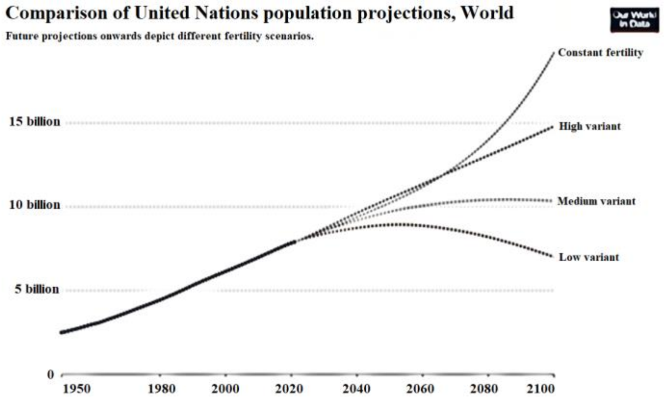

Figure 5. World population, comparison of United Nations projections (https://ourworldindata.org/grapher/comparison-of-world-population-projections)

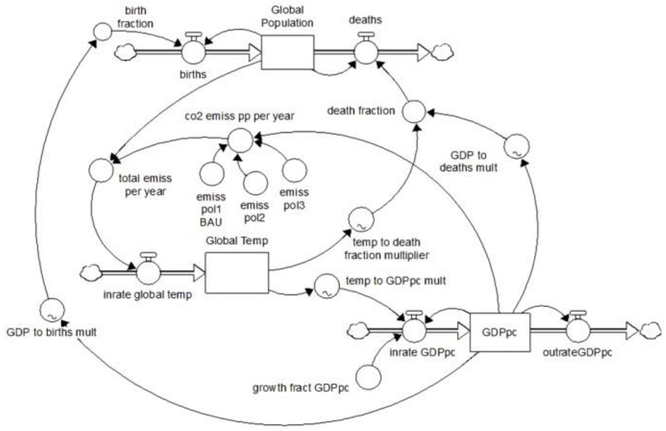

Figure 6. Structure of the SD model (Source: Authors' own elaboration)

The projections rely on the assumption that world fertility levels will continue to decrease with increasing prosperity, with uncertainties restricted to "how much?" Elsewhere sources, including within the UN, have published estimates and concerns as to the likely future impact of increased global temperatures on human welfare and industrial production. Yet such concerns seem to have played no role in the population projections. The model to be developed here specifically considers the potential impact of these interactions.

It is indicated that this graph is freely available for use by those interested.

Model Development

The stock variables chosen for the model are measures of productivity (GDPpc), population (Global_Population) and temperature (Global_Temp). The last 60 years has featured increased industrialization, particularly among nations with emerging economies. Such development is indicated by increases in gross domestic product per capita (GDPpc)–a measure of goods and services produced per member of a population. Increasing GDPpc has been linked directly with reduced birth rates as a result of improved education and living conditions; and with decreasing death rates due to improved health provisions, so leading to impacts on Global_Population. The future impact of increases in Global_Temp on human mortality and industrial development have been argued by organizations such as World Health Organization (WHO, 2021) and the Swisse Re Institute (2021). The three fundamental stocks interact with each other as shown in the complete model diagram in **Figure 6**.

Continuing reference is made to this diagram to support the formulation which follows.

Formulation of Model Equations

We now elaborate the formulation of the model following the selection of the stock variables: GDPpc, Global_Population, and Global_Temp as discussed above. The formulation involves defining other variables driving the growth and decline of these stocks (flows and converters in the model representation)–and the parameter values which instantiate them.

GDP per capita

Dynamically, the current level of GDP per capita (*GDPpc)* facilitates the creation of more. For example existing machinery needs replacement, so generating the need for more and better machinery. The number of well-educated individuals facilitates further increases in following generations, as well as increased productivity, and research and development activities, leading to new products and improved processes. As such the growth of world GDPpc is exponentially driven, as illustrated by reference to the Macrotrends[3] website which provides its annual values from 1960. (The 2020 value is more than twenty times its 1960 counterpart.)

The growth rate of this stock (inrate_GDPpc) is defined as its underlying annual percentage increase (growth_fract_GDPpc) modified by a multiplier (temp_to_GDP_mult) that transmits the impact of future rises in global temperatures on the rate of growth.

Annual values of GDPpc from 1960 are provided on the Macrotrends website. Values in the model are normalized by dividing by the 1960 value of $459. (This to keep values independent of later changes in the currency values used as bases for calculation). The initial model value is therefore normalized to be equal to 1.

Historical values of the annual growth fraction are used from 1960 when the model is initialized: 7.46 % pa from 1960 to 1990, and 3.1% pa for the next 30 years. Beyond 2020, values are chosen to represent reasonable future estimates: 1.9% in most runs based on OECD projections. Lower (1%) and higher (2.5%) values are used for comparison purposes.

In terms of temperature effects the Swiss Re Institute (for example) estimated that impacts of well below 2 ºC increases by 2050 can be contained to 4%; to 11% if further mitigating actions are taken (2 ºC increase); increasing to 14% if some mitigating actions are taken (2.6 ºC increase); and 18% if no mitigating actions are taken (3.2 ºC) increase. (The OECD has warned that without new policies global average temperatures would be projected to rise between 3 and 6 degrees Celsius by the year 2100.)

[3] Macrotrends is a main source of data for the model. Other useful sources are Statista and Worldometer.

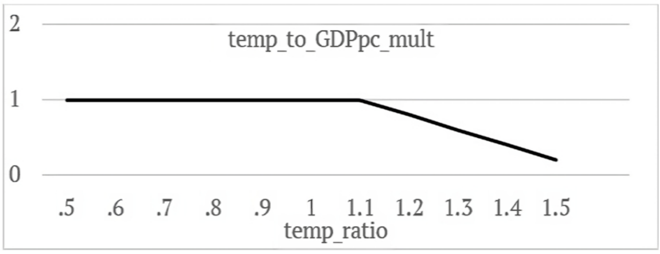

Figure 7. Global temperature to GDPpc multiplier (Source: Authors' own elaboration)

The shape of the multiplier transmitting the impact of increases in global temperature to the rate of growth of GDPpc, is shown in **Figure 7**. The abscissa variable (temp_ratio) is given by global temp/13.9 which is a dimensionless multiple of the 1960 temperature (13.9 degrees C). Small temperature rises are contained, but a steadily increasing impact begins when the global temperature increases beyond 10% of its 1960 value.

It is through multipliers that the non-linear and simultaneous properties of model structure are transmitted. In SD It is not acceptable to omit a process of known significance on the grounds that 'hard data' are not available. Processes are included because they are recognized as important real-world influences not because they are easy to define in terms of quantitative data. To 'omit' such a process on the grounds of insufficient data is not to omit it at all–but to include it with an assigned weight of zero. This is a far more serious structural error than getting the shape of an effect correct, but its detail approximate. Changing multiplier values while retaining the shape of an effect rarely changes the form of the behavior. This is the case here as sensitivity testing confirms.

In summary the equations defining the inrate and outrate to GDPpc are, as follows:

$$inrate\_GDPpc = GDPpc * (1 + growth\_fract\_GDPpc * (0 + 1 * temp\_to\_GDPpc\_mult)). \quad (1)$$

$$outrate\_GDPpc = GDPpc/1 \ (units\ are\ 1/year\ as\ GDPpc\ is\ defined\ to\ be\ dimensionless). \quad (2)$$

For eq. (1), the 1 in the first parentheses has units 1/year. This can be achieved by adding a component "time to update" that contains a value 1 (with units year)and connecting it to inrate_GDPpc and having the 1 in the first parentheses divided by the new component. This was eliminated from the model diagram and equation to maintain simplicity.

Exchanging '0' and '1' in the final bracket of the inrate replaces the assumption of temperature impact with one of no temperature influence (multiplier value = 1). This models the position of global warming skepticism.

Formulation entered by the modeller into the variable dialogue boxes is, as shown in **Figure 8**.

Explanation of boxed content: For the growth_fraction, the first two step functions model the average historical growth figures for the period of 1960 to 1990 and the following 30 years. The third step function adjusts the net growth value to 0.019 year^{-1} in line with an OECD prediction for growth beyond 2020.

INIT GDPpc = 1: Unit: dimensionless.

growth_fract_GDPpc = STEP(0.07469,0) - STEP(0.04369,30) - STEP(0*0.012,60)

Unit: per year (or year^{-1})

temp_to_GDPpc_mult = GRAPH(temp_ratio) Points: (0.5, 1), (0.6, 1), (0.7, 1), (0.8, 1), (0.9, 1), (1, 1), (1.1, 1), (1.2, 0.8), (1.3, 0.6), (1.4, 0.4), (1.5, 0.2)

Unit: dimensionless

inrate_GDPpc = GDPpc*(1+growth_fract_GDPpc*(0+1*temp_to_GDPpc_mult))

Unit: per year (or year^{-1})

outrate_GDPpc = GDPpc/1 : Unit: year^{-1}

GDPpc(t) = GDPpc(t - dt)+(inrate_GDPpc – outrate_GDPpc)*dt (integration performed by the software)

Unit: dimensionless

Figure 8. Formulation of equations defining GDPpc (Source: Authors' own elaboration)

The temp_to_ GDPpc_mult transmits the future impairing impact of increasing global temperature on production of GDPpc (**Figure 7**).

Outrate empties the GDPpc stock, reflecting that it is continuously dissipated and renewed. The division by '1' indicates that this is an annual occurrence, accompanied by its replacement by an augmented value in the following year–as defined by inrate_GDPpc.

#Numerical integration is automatically performed by Stella without user input

Carrying capacity (Global_Population)

Birth fraction and birth rate: Historical data have been used for generating birth and death fractions for the 60 years from 1960 to 2020. Their expression in terms of GDPpc follows the formulation described above which generates GDPpc at yearly intervals.

Beyond 2020 birth rate formulation is predicated on the assumption that fertility levels will continue to fall with further rises in prosperity (measured by GDPpc)–as assumed in the UN projections. It is further assumed that there is a limit to this reduction as otherwise a prosperous world would run out of people. As a middle position the OECD fertility figure of 1.94 by 2100 is taken as this limiting value. Two other scenarios are provided for, being respectively higher and lower than this figure, but less than the current value of 2.4.

Average lifetimes are rising in concert with levels of GDPpc, and these influence birth fractions expressed in terms of population percentages. For example, assuming that an average lifetime reaches 80 years by 2100, then taking the UN predicted fertility value of 1.94 at this time, and assuming that the population is equally divided between males and females, means that 0.97 new persons are created per person over a period of 80 years–a birth fraction of 0.97/80 = 0.012125 (persons/year)/person or 0.012125 year^{-1}. (For a population of 1000 persons this would generate a birth rate of 1000 *0.012125 = 12.125 persons/year.)

A value of 0.012 is chosen to reflect this mid-case scenario, paired with an assumed future average lifetime of 80 years. Other magnitudes of birth fraction tuned to this assumed lifetime are provided for use in alternative scenarios: 0.014 (fertility level of 2.24), and 0.010 (fertility level of 1.6). Other values can be chosen at the modeller's initiative.

A multiplier (**Figure 9**) is used to modify the 1960 birth_fraction value of 0.0354 year^{-1} to reflect the historical

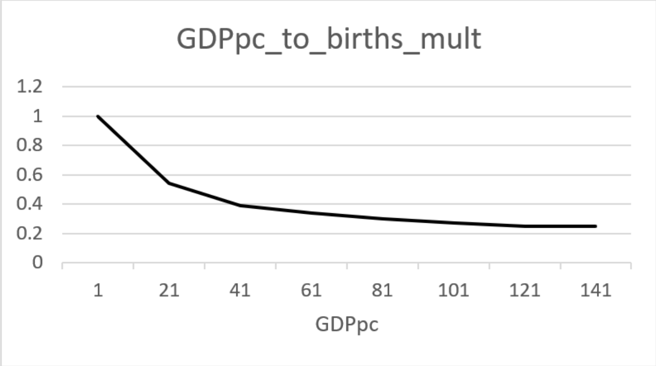

Figure 9. GDPpc to birth fraction multiplier (Source: Authors' own elaboration)

values from 1960 to 2020, and then to provide smooth transitional values to the future limiting value(s) described above.

The dimensionless abscissa variable (GDPpc) begins at its 1960 value of 1 and is continued beyond the time when the decreasing value of the multiplier (in the absence of temperature effects), causes the resulting value of the birth fraction to reach its chosen limiting value of 0.012. See expression for birth_fraction above. The equal spacing of values of the abscissa variable is a consequence of the software specification of table functions.

Death fraction and death rate: Published statistics since 1960 contain huge variations reflecting two underlying processes simultaneously at work. Firstly, the increase in births from the middle of the 20th century means that a "younger bulge" has been moving through the population, reducing the percentage death rate compared with that which would apply if all age groups were proportionally represented. Secondly, in parallel with this circumstance, there have been major advances in health and nutrition, especially in countries enjoying greater prosperity, through increasing GDP per capita. Consequently average lifetimes have increased greatly as confirmed by reference to life expectancy tables. Both these factors need to be considered when projecting future population numbers from past trends.

Historical data (Macrotrends) are again used for the sixty years from 1960 to 2020. As already noted future projections assume that the fall in birth fraction will continue with increasing prosperity, leading to a future in which the death fraction reaches a stable value approximately an average lifetime after the birth fraction stabilizes.

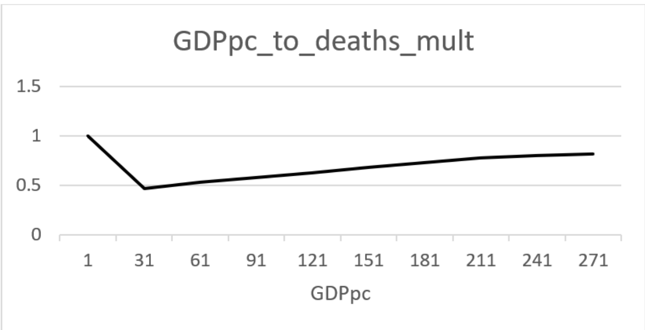

Figure 10. GDPpc to death fraction multiplier (Source: Authors' own elaboration)

A multiplier (**Figure 10**) is used to modify the 1960 death fraction value of 0.0169 $year^{-1}$ to reflect historical values from 1960 to 2020, and then to provide smooth transitional values to a future value of 0.0125 which corresponds to an average life expectancy of 80 years. Values corresponding to average lifetimes of 75 and 85 years are also provided for use in alternative scenarios.

At first sight this multiplier has an unusual form. The initial decrease is substantially due to the birth boom from the 1960s–reducing the average death fraction value in the population at large, because of a younger cohort that takes an average lifetime to work its way through. Improved health spending has also had a positive effect on longevity. Data (e.g., Macrotrends) indicate that the minimum has been recently reached as the bulge has progressed, but its continuing impact means that the average death rate is still substantially lower than that corresponding to a life expectancy of 80 years. The steadily increasing multiplier reflects that the death rate will continue to increase slowly as the population reaches a stable profile. However improved health under increased prosperity means that its value will stabilize as explained in the formulation that follows later. So for this multiplier the early section contains values that reflect historical phenomena, while the later section describes an approach to a future stabilized life expectancy. Abscissa values extend substantially further than in **Figure 9**. This is because death fraction limiting values are not reached until a lifetime after birth fraction values stabilize.

Consistent with the assumptions of this model a further multiplier is used to transmit an influence that has been absent from past projections - the impact of increasing global temperature on death fraction. According to the New Health Data Explorer, exposure to life-threatening heat waves will increase by 350% for vulnerable age groups at 1.5 °C increase, 2,510% at 2 °C , and 6,310% if no climate action is taken. So as discussed earlier, increased temperatures are predicted to impact on human welfare and mortality, both directly through heat related illnesses, and indirectly through increased water shortages, harsher living conditions, and unpredictable 'climate events'.

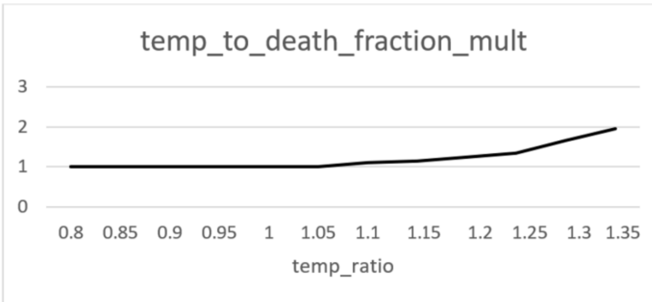

Figure 11. Global temperature to death fraction multiplier (Source: Authors' own elaboration)

The "temp to death fraction" multiplier is displayed in **Figure 11**. Its values are paired with the ratio of global temperature to its 1960 value of 13.9 degrees C. The impact is assumed to begin when the temperature rises beyond 10% of its 1960 value, rising at first gradually and then more sharply as the ratio reaches higher values.

```
INIT Global_Population = 3 019 233 434 Unit: persons

birth_ fraction = MAX(0.0354*GDPpc_to_birth_mult,0.012)  Unit: per year (or year-1)

GDPpc_to_births_mult =  GRAPH(GDPpc) Points: (1.0, 1.0000), (21.0, 0.5400), (41.0, 0.3900), (61.0, 0.3400), (81.0, 0.3000), (101.0, 0.2700), (121.0, 0.2500), (141.0, 0.2500)

Unit: dimensionless

births = Global_Population*birth_fraction    Unit: persons/year

death_fraction = IF TIME<=60 THEN GDPpc_to_death_mult*0.0167 ELSE MIN(GDPpc_to_death_mult*0.01687,0.0125)*(0+1 * temp_to_death_fract_mult)

Unit: per  year  (or year-1)

GDPpc_to_deaths_mult = GRAPH(GDPpc) Points: (1.0, 1.0000), (31.0, 0.4680), (61.0, 0.5280), (91.0, 0.5800), (121.0, 0.6300), (151.0, 0.6800), (181.0, 0.7300), (211.0, 0.7800), (241.0, 0.8000), (271.0, 0.8200)

Unit: dimensionless

temp_to_death_fraction_multiplier = GRAPH(temp_ratio) Points: (0.8000, 1.0000), (0.8500, 1.0000), (0.9000, 1.0000), (0.9500, 1.0000), (1.0000, 1.0000), (1.0500, 1.0000), (1.1000, 1.1000), (1.1500, 1.1500), (1.2000, 1.2500), (1.2500, 1.3500), (1.3000, 1.6500), (1.3500, 1.9500)

Unit: dimensionless

deaths    = Global_Population* death fraction              Unit: persons/year

#Global_Population(t) = Global_Population(t - dt)+(births - deaths)*dt

(integration as performed by software) Unit: persons
```

Figure 12. Formulation of equations defining Global_Population (Source: Authors' own elaboration)

There is no limit to the number of alternative graphs that can be developed to provide for varied assumptions.

In summary the equations defining the inrate and outrate to Global_Population are, as follows:

$$Births = Global\_Population * birth\_fraction \text{ where } birth\_fraction = MAX(0.0354 * GDPpc\_to\_birth\_mult, 0.012)\ (persons/year). \quad (3)$$

$$Deaths = Global\_Population * death\ fraction \text{ where } death\_fraction = IF\ TIME \leq 60\ THEN\ GDPpc\_to\_death\_mult * 0.0167\ ELSE\ MIN(GDPpc\_to\_death\_mult * 0.01687, 0.0125) * (0 + 1 * temp\_to\_death\_fract\_mult). \quad (4)$$

Exchanging '0' and '1' in the final bracket of the death fraction alters the scenario from one in which global warming is included as a factor impacting on human welfare to one in which it is not–a denialist position. The formulation entered by the modeller into the variable dialogue windows is as shown in **Figure 12**.

Explanation of boxed content: The variable 'births is' defined as the product of Global_Population and birth_fraction. The birth_fraction is defined in terms of historical data for the period 1960 to 2020 (TIME ≤ 60). After 2020 it is assumed to continue to decrease with increasing prosperity (GDPpc), reaching a limiting value of 0.012 as described in the earlier discussion. (Refer **Figure 9** for the graphical representation of the multiplier).

Similarly the death_fraction is defined in terms of historical data for the period 1960 to 2020 (TIME ≤ 60). Its later values reflect an approach to a limiting value of 0.0125, corresponding to an average lifetime of 80 years. This behavior is represented by the values of the multiplier in **Figure 9**.

Subsequent to 2020 the death fraction is also impacted by increasing global temperature (Global_Temp). This effect is contained in the multiplier values shown in **Figure 11**.

World temperature (Global_Temp)

Reference to the model diagram in **Figure 6** shows that inrate_global_temp is defined in terms of total emissions of CO_2. Strong exponential growth in both population and industrialization since 1960 implies an anthropogenic basis for linking total CO_2 emissions with global temperature change during the time period from 1960 to 2020. Therefore, an exponential trendline was applied to model NASA [4] temperature change data during this time period. The resulting formulation was $T = 13.75e^{0.0011t}$. The actual global temperature(T) from the data table for 1960 was 13.9 °C, so a temperature of 13.9 °C was used as the initial value in the Global_Temp stock. From this formulation the average annual increase in temperature can be estimated on a yearly basis.

The Macrotrends[5] website contains global data for total CO2_emissions_per_year, so using the above estimates of temperature change, sets of values pairing temperature change per year, with total emissions per year were obtained for the time period 1960 to 2020. The correlation between the two data sets is 0.99, and a formula linking the data is obtained via spreadsheet, as follows:

$$inrate\_global\_temp = 0.014945 + (0.00003744/10^9) * total\_emiss\_per\_year). \quad (5)$$

Note that the units of the respective terms are degrees C/year, so the unit of the numerical coefficient in the last term is degreesC/tonne - as tonne is the unit for emissions in the model. (The mathematical form of the coefficient (featuring $10^{9)}$ reflects that website data expresses emissions in billions of tons.)

In the model total_emiss_per_year = CO2_ emiss_pp_per_year * Global_Population, where CO2_emiss_pp_per_year is defined in terms of levels of industrialization GDPpc.

Corresponding yearly values of these last two quantities are available from the Macrotrends website, and they are strongly correlated (approx. 0.8). Individual vagaries occur in various years - for example in 1989-90 around the collapse of the USSR, in years affected by the GFC crisis, and COVID-19 lockdowns. Some zigzagging occurs here and there, probably influenced by where growth is strongest at a given time, as some major global contributors differ in the efficiency of their processes. So regression as a basis for future projections does not seem so safe or useful here.

Instead developing linear relationships that capture the joint behavior of the variables, and testing output for sensitivity has been used. The simplest is the line joining (1, 3.11) to (23.83, 4.5) which are the respective values in 1960 and 2020, giving CO2_emiss_pp_per_year = 3.049 +0.06088*GDPpc (tons/person/year).

Another choice was guided by the general gradient of a line of best fit (EXCEL generated) beginning at (1, 3.11)–the 1960

[4] https://climate.nasa.gov/vital-signs/global-temperature/?intent=121
[5] https://www.macrotrends.net/global-metrics/countries/WLD/world/carbon-co2-emissions

```
INIT Global_Temp(t) = 13.9     Unit: degrees C
CO2_emiss_pp_per_year     IF TIME<=60 THEN (3.049+0.06088*GDPpc) ELSE
(emiss_pol1*(3.049+0.06088*GDPpc) +emiss_pol2*4.5 +emiss_pol3*MAX((3.049+0.06088*GDPpc)*EXP(-
.04*(TIME -60)),0.5))
Unit: tonnes/person/year
total_emiss_per_year = Global_Population*CO2_emiss_pp_per_year   Unit: tonnes/year
inrate_global_temp          = 0.01495+(0.00003744/10^9)*total_emiss_per_year
Unit: degrees C/year
# Global_Temp (t) = Global_Temp (t - dt) + (inrate_global_temp)*dt.
(integration as performed by software.) Unit: degrees C
```

Figure 13. Formulation of equations defining Global_Temp (Source: Authors' own elaboration)

values. This gives CO2_emiss_pp_per_year = 3.06 +0.045*GDPpc (tons/person/year).

When tested in the model, comparative output graphs are indistinguishable, so in model formulation the former is used. Referring to **Figure 6**, it now remains to specify policies aimed to mitigate the effects of rising temperatures. (Sometimes a goal of a model is to find measures that ensure as far as possible that its predictions never eventuate!)

Policies ask what happens if particular issues are addressed in certain ways. While a model is not usually equipped to decide whether suggested actions are practically feasible, it can focus attention on where effort might be most effective. Three policies are included in the present model, focused on the level of emissions of CO2 being produced in terms of their potential impact on temperature change. They are displayed in **Figure 6** as emiss_pol1, emiss_pol2, and emiss_pol3. As indicated in the formulation which follows they are designed to operate separately as alternatives.

Emission policy1: This is business as usual (BAU) with emissions continuing to be produced at the rate that has been identified with activity since 1960, as given by the formula:

$$CO2\_emiss\_pp\_per\_year = 3.049 + 0.06088 * GDPpc\ (tons/person/year). \tag{6}$$

Emission policy2: This policy asks what would be the effect of freezing the level of emissions per capita at their 2020 level of approximately 4.5 tons/person/year?

Emission policy3: This policy applies an emission reduction policy that exponentially reduces emissions per capita from their 2020 value of approximately 4.5 tons/person/year, to 0.5 tons/person/year, over a period of 25 years. (It is assumed that some residue will remain, and 0.5 is chosen as this arbitrary minimum.) In the model formulation, the policies are subsumed as alternatives in the expression for CO2_emiss_pp_per_year. (See further note on activating policies in **Figure 13**). Putting together the above, the equations defining the inrate to Global_Temp (in degrees C/year) are, as follows:

$$inrate\_global\_temp = 0.01495 + (0.00003744/10^9) * total\_emiss\_per\_year, \tag{7}$$

where

$$total\_emiss\_per\_year = Global\_Population * CO2\_emiss\_pp\_per\_year, \tag{8}$$

and

$$CO2\_emiss\_pp\_per\_year = IF\ TIME <= 60\ THEN\ (3.049 + 0.06088 * GDPpc)\ ELSE\ (emiss\_pol1 * (3.049 + 0.06088 * GDPpc) + emiss\_pol2 * 4.5 + emiss\_pol3 * MAX((3.049 + 0.06088 * GDPpc) * EXP(-.04 * (TIME - 60)), 0.5)). \tag{9}$$

The formulation entered into the variable dialogue box windows is as in **Figure 13**.

Explanation of boxed content: In addition to the information provided before **Figure 13**, policy 1 (business as usual) is activated by setting emiss_pol1 =1, and emiss_pol2 = emiss_pol3 = 0 in the respective variable dialogue boxes. Correspondingly respective allocations of (0, 1 , 0) and (0, 0, 1) are used to activate policy 2 and policy 3.

Alert: To stay within the limits of the free software version a single converter is used for the following formula:

$$inrate\_global\_temp = 0.014945 + (0.00003744/10^9) * total\_emiss\_per\_year). \tag{10}$$

With unlimited variables each component would be assigned a separate converter. Because of the mixed units in the formula (see eq (10)) a unit warning is issued by the software in circumstances like this. This can be ignored when these circumstances apply.

FEEDBACK PROCESSES

The behavior of SD models is controlled by system feedback determining how the different entities in the model interact. This can be appreciated by following closed circuits of causal activity around the diagram in **Figure 6**. While any loop variable can be chosen as a starting point for describing what ensues when the value of the variable initially increases or decreases, it is customary to begin at a stock variable as below.

Loop 1 (Refer Figure 6)

This loop traces the impact of GDPpc back on itself through the loop which works its way through emissions, and Global_Temp. An increase in *GDPpc* increases *CO2_emiss_pp_per_year*, leading to an increase in *total_emiss_per_year*. In turn this causes an increase to *inrate_global_temp,* and thence to an increase in *Global_Temp*. This increase reduces the value *of* the *temp to GDPpc_mult* (as production of GDP is impaired by rising temperature), and thence to a reduction to *inrate_GDPpc*. This reduction means that *GDPpc* will increase less than it would have increased if its inrate had not been decreased by the impact of increasing temperature. We see that an initial increase in GDPpc leads to a reduced increase in the same quantity as the circuit is completed, thus mitigating the growth of GDPpc. This is an example of a balancing loop.

Loop 2 (Refer Figure 6)

This loop traces the impact of a change in GDPpc back on itself through the loop which works its way through Global_Population, and Global_Temp. All three stocks are represented in this loop. An increase in *GDPpc* leads to a reduction in the *GDPpc_to_births_mult* (reflecting the downwards pressure of increasing GDP on fertility levels), resulting in a reduction in the *birth_fraction,* and thence in *births*. The reduction in *births* means that the *Global_Population* will be less than it would have been had the *births* not been decreased. In turn this relatively lower population leads to a lower value of *total emiss_per_year*, which leads to a smaller increase in the *inrate_ global_ temp,* and thence slows the rise of *Global_ Temp*. The resulting lowered value of *Global_Temp* causes less reduction in the value of the *temp_to_GDPpc_mult* (by mitigating temperature stress on production of GDP). The *inrate_GDPpc* is thus decreased less, so leading to a relative greater increase in the value of *GDPpc* than if this temperature decrease had not occurred. We see that an initial increase in GDPpc has led to a relative increase in the same quantity as the circuit is completed. This is an example of a reinforcing loop.

Loop activity is at the heart of why the solution of "wicked problems" is so challenging. Here the variable GDPpc occurs on two loops (there is a third) with counter intuitive behavior. It is a major reason why intuition is unreliable when dealing with complex systems–a policy that seems sensible in one part of a system can turn out to be counterproductive elsewhere.

Two further balancing loops can be identified. Loop 3 can be traced from *Global_Population* through *total_emiss_per_year*, and thence via temperature variables back to *Global_Population* through the *temp_to_deaths mult*. Loop 4 is parallel to Loop 2 where the impact of changing *GDPpc* is channelled through its influence on deaths rather than births.

MODEL OUTPUT

Figure 14 shows output for the stocks of Global_Population, Global Temp, and GDPpc. Differential scaling enables them to be shown on the same diagram. Real historical data are superimposed from 1960 to 2020, and the model output tracks these data over this period. Beyond 2020 model output projects future values up to a chosen time horizon of 2200.

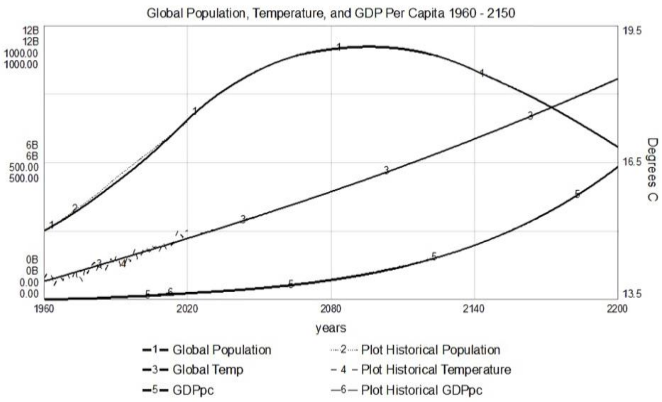

Figure 14. Stella output showing values of the three stock variables (Source: Authors' own elaboration)

Population Projections for Different Birth Fractions

Figure 15 contains comparative graphs for population projections under different fertility (birth fraction)

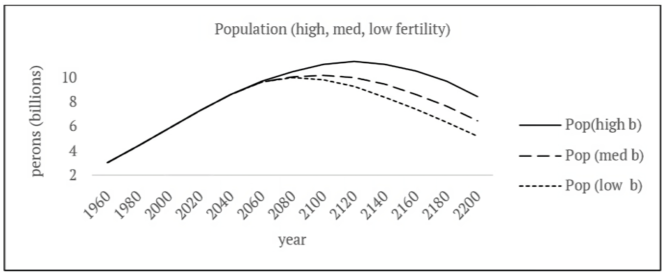

Figure 15. Model population projections to 2200 for different fertility assumptions under business as usual conditions (no emission reductions) (Source: Authors' own elaboration)

assumptions. It is produced by creating an EXCEL graph from numerical data copied from successive model runs. The output invites comparison with the corresponding UN projections in **Figure 5**.

Comparing the model graphs in **Figure 15** up to the year 2100 (under the business as usual policy) with those in **Figure 5** we note the following:

Both medium births scenarios generate values within about 1 billion of a 10 billion population projection and are close to horizontal in 2100. The higher births UN projection is continuing to show strong upward growth, while the corresponding model graph is trending concave down. Both of the lower projections feature downward concavity at this time.

Considering model graphs beyond the year 2100 suggests that using a cut-off time of 2100 may mask some fundamental differences associated with the way the projections have been generated. Downward concavity in the low births UN scenario is due to replacement of the population bulge caused by higher birth rates in the mid-20th century whereby lower subsequent birth rates (caused by lowered fertility values) cannot maintain the population after the bulge has been dissipated by natural causes.

In the model, downward concavity of population graphs is featured in all birth scenarios (high, medium, and low) and is more pronounced. While reduced birth rates remain a factor their effect is enhanced by the impact of feedback from rising global temperatures, which increases the mortality rate for all birth rate variants.

Temperature Impacts Denied

Figure 16 contains model output when the impacts of temperature effects on mortality and generation of GDP per capita are switched off. This scenario represents global warming skepticism/denial, in which there is no feedback from emissions to influence either global temperature or population.

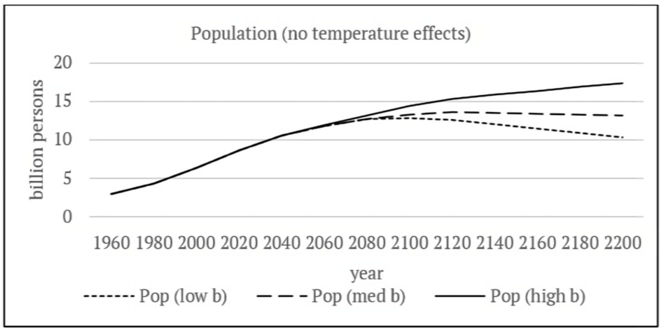

Figure 16. Model population projections to 2200 for different fertility assumptions with temperature effects removed (Source: Authors' own elaboration)

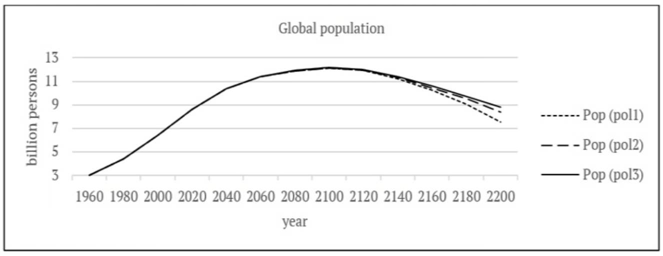

Figure 17. Model population projections under CO2 policies 1 to 3 (Source: Authors' own elaboration)

The graphs have the form that the UN graphs would take if the trajectories of the latter were to be extrapolated beyond the year 2100. This is consistent with an approach to population projections which incorporates assumptions about different levels of fertility, without considering the impact of rising temperatures. It begs the question as to why global warming, while accepted as an alarming phenomenon to be minimized, does not appear to be factored into carrying capacity predictions. How then is this different from predictions that would be made by global warming deniers?

In terms of implications, comparison between **Figure 15** and **Figure 16** can be used in a number of ways. One approach is to take respectively the positions of those accepting and denying the anticipated effects of global warming. Pointing to **Figure 16** sceptics might argue that vast resources stand to be potentially wasted in preparing for an eventuality that will not happen. And that such resources will be needed to service the higher Global_Population that will eventuate. The other side can point to implications from **Figure 15** concerning the human cost of getting things wrong. Billions will suffer if expectations of global warming impacts are fulfilled, with the predicted downturn in population reflective of this outcome.

Policy Analysis

The three diagrams in **Figure 17**, **Figure 18**, and **Figure 19** compare the values of the three stocks under the respective conditions of: Policy 1 (continued growth in emissions per capita–business as usual); Policy 2 (future emissions per capita are capped at 2020 levels; Policy 3 (future emissions per capita are reduced to one quarter of their 2020 levels over twenty five years and then continue at the reduced level), respectively. For these scenarios a medium limiting birth fraction of 0.012 year^{-1}, and an average lifetime of 80 years are assumed, together with a future growth rate of GDPpc of 1.9% per annum.

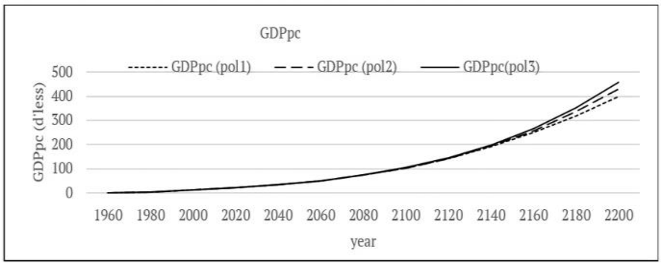

Figure 18. Model GDPpc projections under CO2 policies 1 to 3 (Source: Authors' own elaboration)

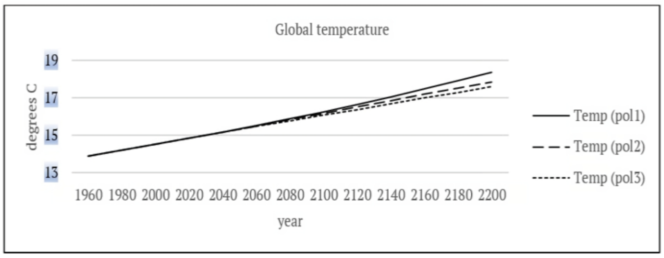

Figure 19. Model global temperature projections under CO2 policies 1 to 3 (Source: Authors' own elaboration)

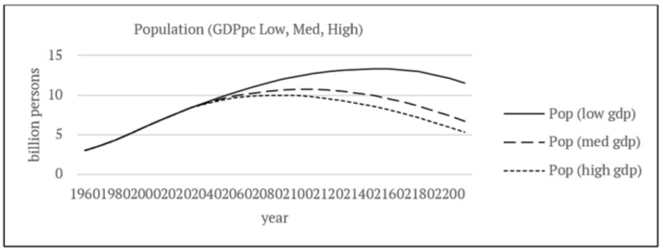

Figure 20. Population at different rates of GDPpc growth (Source: Authors' own elaboration)

Taken together these graphs can be viewed as an aspect of model evaluation, as well as providing problem relevant outcomes. The model is doing what it should in that

(1) population values, temperature effects, and values of GDPpc are in the expected order according to strength of emission reduction policies and

(2) outcomes are consistent with inbuilt feedback influences e.g., the highest global temperature is associated with the lowest population.

Exploring Other Outcomes

Model behaviors other than those most relevant to the main question can serve a useful purpose. **Figure 20** contains output for population levels under different assumptions of GDPpc growth, assuming business as usual conditions.

Growth rates of GDP per capita beyond 2020 are respectively low (1%); medium (1.9%); high (2.5%). It will be noted that the size of the corresponding populations are in inverse relationship to these rates. For example, the lowest rate of growth (1%) leads to the highest population.

While such outcomes may seem counterintuitive, they are consistent with the impact of the feedback structure. The behavior is dominated by the influence of a feedback loop which is responsible for the impact of GDP_per_capita on birth_fraction, and thence on population. At a high rate of GDP_per_capita growth (rapidly increasing global prosperity) the downward pressure on birth_fraction acts swiftly to continue to depress the average birth_fraction, which quickly reaches a limiting value. This effect flows through to curtail population growth. The outcome is a smaller world population with a high standard of living.

At the lowest level of growth (1%), GDP_per_capita growth is subdued, so that average global fertility levels remain higher for longer, resulting in a correspondingly higher population. The outcome here is a higher population with a lesser standard of living. By the same logic, the medium growth rate leads to an intermediate population size. The same relative outcomes apply across all emission policies.

In terms of the IM^2C problem expectations of a single solution need to be reviewed. Outcomes are influenced heavily by model assumptions, which are themselves based on system conditions that admit a range of possibilities. UN population projections reflect this, but only in terms of their dependence on different assumptions about future fertility levels. In this model impacts of rising global temperatures on industrial development and human mortality are included as additional interacting factors.

Many more simulation experiments can be undertaken, for example to explore potential outcomes if UN assumptions about future fertility rates turn out to be far from the mark, or the effect of rising temperatures on productivity and human health have been underestimated in the present model runs. The present model provides for all such scenarios to be included as variations within its structural formulation. New insights that emerge (often unforeseen) are more akin to the outcomes of applied mathematical research than to those from classical mathematics education investigations.

It was noted that in addressing the original IM^2C problem, student teams did not consider that diminishing resources would interact with each other and with population. In the absence of appropriate modelling software they were not equipped to address the problem in the way expected. The method used in the current model would enable such an approach. Instead of population, temperature, and industrial development being linked in non-linear relationships by means of multipliers, interactions between population, food supply, land for agriculture, non-renewable resources…would be so linked. It should be noted however that a full version of Stella would be needed, as the model would be too large for the free version. It can be noted with pleasure that during 2023 a free full version of the software has been offered to schools worldwide whose coverage extends across K - 12 educational levels.

EDUCATIONAL REFLECTION

Consciousness of limits on working memory underpins the whole edifice of SD modelling. Humans are good at describing and making decisions about matters in their immediate environment. They are not well equipped to trace the outcome of a bunch of decisions involving interactions between variables only some of which they may be able to control. The reason for this is the combination of feedback loops (four major loops in this model), in producing simulation output. It was noted earlier that different impacts were provided by two of the loops containing GDPpc, and the strength of loops varies over time. The software (with unlimited memory) enables interactions and consequences of assumptions to be accurately traced over any time period, so generating output that faithfully represents the combined implications of the individual decisions underpinning the model formulation.

STUDENT WORK

While no student work is available for the carrying capacity model, examples of SD modelling using Stella software are instructive in illustrating the accessibility of the modelling process. The second author (while a teacher) worked extensively with class groups of secondary students in normal school settings in supervising projects involving the application of SD. While some required full versions of Stella, the modelling principles and methods are the same, irrespective of model size. As in the carrying capacity model, substantial problems were modelled using the free software version.

The following examples provide a sense of the scope of projects undertaken by students.

- Can automakers cope with increasing demand for hybrid-gasoline electric vehicles?
- How does the workforce of a company respond to changes in demand?
- How do breaches affect airport security?
- How does the level of GABA in the synapse affect the rate of receptor binding and thus affect the depth of anesthesia a person may feel?
- If a tree falls in the forest, will another replace it?

And following **Figure 21** extended samples of work illustrate the kinds of thinking displayed by students using two further project contexts.

Figure 21 contains a summary of the advice provided to students as guidelines for developing and reporting a SD modelling project of the type described in Fisher (2018). It will be recognized that its contents contain advice applicable to the development and reporting of any SD project.

A significant feature in terms of school learning is that the modelling of growth and decline of stocks represented as rectangles (containers), by means of flows (represented as valves), means that students become comfortable with formulating equations that in other approaches would involve calculus concepts and procedures. So modelling is accessible to students initially at the pre-calculus stage of their education, as well as at more advanced levels.

Excerpts from two student projects follow and full project reports may be accessed through the links provided.

Sample problem 1: *Is vehicular pollution a pending crisis?*

Below is a reduced version of the introductory statement developed by Lorelle (pseudonym) to motivate her project:

A. Introduction

What is the question or problem you are investigating? Tell the story of the problem, and why we should be interested. What will a model tell you that cannot easily be learned other ways?

B. The process of model building

Write a story of your modelling process moving from your first model diagram to your final model diagram.

C. Walk the reader through your final model

Design the story so an intelligent novice (someone with a little knowledge of stocks and flows) could understand it. You will want to talk about how the pieces interact, how the equations were set up, how values of parameters were chosen, and why you have confidence in the structure.

D. The model feedback and loop story

Use loops (one or two), as appropriate, to explain key model behaviours. Trace each loop explaining how each component affects the next and whether the feedback is reinforcing or balancing and why. Describe how the feedback affects the whole system.

E. Model testing

Explain the progression of experiments/simulations you made on your model to give you confidence that it behaves as it should. Discuss any sensitivity analyses you performed and show an example.

F. The results

What do the graphs and tables tell you about the model you tested and the problem you studied?

Explain the output graph(s) and why you chose to graph what you did.

Explain what each curve tells you based on how you understand the system.

In an appendix, include the fully documented equations, with units, the full model diagram, graphs, and tables.

Figure 21. Extended samples of work (Source: Authors' own elaboration)

> Approximately three million people die each year from air pollution, as opposed to one million from traffic fatalities, according to the World Health Organization, and vehicle emissions provide the pollution responsible for about half of those deaths. Yet all over the world vehicle fleets continue to grow, making urban areas frighteningly congested, consuming more fuel, and adding more and more pollution to the environment. It is argued that increasing demands for products that pollute the environment (following population growth), increase the concentration of pollutants, which in turn impacts on population.
>
> Such a scenario is not unlikely at the rate that the world is developing, and there is no easy way to slow down or halt the advance of this crisis. On a macroscopic scale, the most efficient way to attempt a change could be to make pollution very unprofitable for industry, rather than attempting to change people's minds about the environment. Changing minds, however, can be a powerful thing, and in order to gain a personal understanding of the situation I built a Stella model of the relationship between population, vehicles, and carbon monoxide pollution.

The resulting student built model contains three stocks: population, vehicle numbers, and level of carbon monoxide emissions. The population death rate is defined to be affected by the concentration of carbon monoxide (via a multiplier), as well as by population density. The level of carbon monoxide emissions is determined by the number of vehicles, and the number of vehicles by population numbers. So the interdependence of the stocks is defined through model equations that reflect the non-linearity and simultaneity thus incorporated.

In terms of the benefits of modelling the student made the following reflective comment:

> The model was not ultimately successful in answering the question put above, that is, whether vehicular pollution is ultimately sustainable in terms of population, but in the process of model building I gained an invaluable understanding of what it means to build a model and of the dynamic relationship between pollution and population.

It is often the insights gained through the model building process that provide some of the main benefits, whether or not the original goal has been achieved as planned. The full modelling report can be accessed via the link https://ccmodelingsystems.com/wp-content/uploads/2018/01/VehicularPollutionPaperNarizny.pdf

Sample problem 2: *How does bee colony collapse disorder affect the almond industry?*

Introduction of problem by John (pseudonym):

> Since the 1980s bee colonies have been plagued by various diseases, parasites, and pesticides that have caused a decline in the population of bee colonies. The decline in the bee colonies was gradual until 2006 when farmers and beekeepers noticed a dramatic decline in the number of bee colonies. Researchers have labeled this decline as colony collapse disorder (CCD) and it is characterized by an absence of adult bees in the hive and a live queen bee in the hive. Scientists have been unable to determine a specific cause for CCD. Bees are necessary to pollinate almost all crops. In the United States it is estimated that bee pollination increases the value of crops by $15 billion each year. Some crops, such as the almond crop, are particularly affected as almond trees can only be pollinated by bees. The number of bee colonies directly affects the productivity of the almond trees. CCD is devastating to the agriculture industry, as there is no substitute to bee pollination.
>
> The model is built to generate the following real-world behaviour. The population of bee colonies decreases at an increasing rate as CCD spreads throughout the farms, and the price of almonds increases significantly as the population of bee colonies declines - as there is no substitute to pollination by bees. The price reaches

> an approximate steady state value after a long time as there is a limit to the price that people will pay for almonds.

John's reflection on insights obtained from model:

> Colony collapse disorder can affect the entire almond industry. It could decrease the ability of farmers to supply almonds which means that farmers will have to make changes in order to meet demand. It is possible that these methods will exacerbate CCD and further reduce the population of bee colonies. If farmers disregard the environment it could eventually wipe out enough bee colonies that it would no longer be economical to farm almonds. The several tests that we did on the model show that it is possible for farmers to take measures to prevent the effects of CCD. When farmers or other people create more bee hives this increases the population of bee colonies and creates more bees to pollinate more crops. Farmers may also be able to affect the population of bee colonies by controlling the pesticide use per acre. If farmers reduce their pesticide use our model predicts that the population of bee colonies will increase. Through a few simple modifications the model could be amended to see the effects of CCD on any part of the farming industry or even the farming industry as a whole.

The full modelling report can be accessed via the link https://ccmodelingsystems.com/wp-content/uploads/2018/01/ColonyCollapseDisorderPaperIA.pdf

These excerpts from student work, together with their full modelling reports, illustrate how these students were able to identify a problem amenable to the use of on-line SD software, and build models to understand and address their implications. Further support for SD modelling geared to school learning can be obtained by accessing the link provided by Creative Learning Exchange (2024).

AFTERWORD

The underlying motivation behind this paper is anchored in national priorities to equip future citizens with life-long skills that can be applied to enrich and deepen workplace activity, personal problem solving, and engagement as productive citizens. More than ever the last of these has come to involve notions of global citizenship.

One of the most urgent themes engaging this latter priority is the sustainability of the world population, encompassing concerns about the consumption of essential resources, and the emergence of issues associated with global warming. The IM^2C carrying capacity problem served to underline educational challenges in addressing such problems, when it transpired that none of the teams entering the competition could fashion an appropriate approach to the problem set.

As a typical "wicked problem" where non-linearity and simultaneity among model equations is endemic, a goal of this paper has been to introduce and employ a recently available and accessible methodology that can be applied to address problems of this genre.

As an illustration a modelling approach to the carrying capacity problem has been designed and implemented in full. As the intention is to enable interested readers (and their students if applicable) to apply the methodology independently to other problems, all essential details of the modelling have been provided. The model can be reproduced by anyone with access to the free version of Stella Online.

Effort to understand the methodology and apply the software in building models is of course needed - parallel to that which applies to learning and practicing the capability of any new software such as EXCEL or a CAS program package. More than cursory attention is required, hence if educational provision is in mind, a suggested location lies within the mathematical component of a pre-service teacher education course, and/or as an option within a coursework higher degree. Or of course achieved by individual study as is common among those interested in new technologies. Similarly the goal of student competence with the methodology requires persistence to achieve.

If national bodies are serious in their goal of preparing citizens to address genuine real-world problems, then preparation for global citizenship means providing them with capabilities to deal with "wicked problems" of the type described here. That students in some innovative programs have already proved themselves able to identify such problems and develop solutions to address them, acts as both an inspiration and a challenge.

Author contributions: All co-authors have been involved in all stages of this study while preparing the final version. They all agree with the results and conclusions.

Funding: No funding source is reported for this study.

Ethical statement: The authors stated that the study does not require approval from an ethics committee. No human subjects or animals were involved in research associated with this study.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from corresponding author.

REFERENCES

ACARA. (2017). Introduction. *Australian Curriculum Assessment and Reporting Authority*. https://www.acara.edu.au/curriculum

Creative Learning Exchange. (2024). *Creative learning exchange*. http://www.clexchange.org/

Fisher, D. M. (2018). Reflections on teaching system dynamics modelling to secondary school students for over 20 years. *Systems, 6*(2), Article 12. https://doi.org/10.3390/systems6020012

Forrester, J. (1969). *Urban dynamics*. Productivity Press.

Galbraith, P. L. (2024). Modelling, teaching, reflecting: What more I have learned? In H. S. Siller, V. Geiger, & G. Kaiser (Eds.), *Researching mathematical modelling education in disruptive times. International perspectives on the teaching and learning of mathematical modelling* (pp. 137-147). Springer. https://doi.org/10.1007/978-3-031-53322-8_10

Garfunkel, S., Niss, M., & Brown, J. (2021). Opportunities for modelling: An extra-curricular challenge. In F. Leung, G. Stillman, G. Kaiser, & K. Wong (Eds.), *Modelling education in east and west* (pp. 362-375). Springer. https://doi.org/10.1007/978-3-030-66996-6_30

IM^{2}C. (2024). *The international mathematical modeling challenge*. http://www.IM2Challenge.org/

Isee Systems. (2024). *Access to free Stella Online*. https://www.iseesystems.com/store/products/stella-online.aspx

Meadows, D. H., Meadows, D. L., Randers, J., & Behrens, W. W. (1972). *The limits to growth: A report for the club of Rome's project on the predicament of mankind*. Universe Books. https://doi.org/10.1349/ddlp.1

National Governors Association. (2010). *Common core state standards for mathematics*. National Governors Association Center for Best Practices & Council of Chief State School Officers.

OECD. (2021). *Description of mathematical literacy for 2021*. https://www.oecd.org/pisa/pisaproducts/pisa-2021-mathematics-framework-draft.pdf

Swisse Re Institute. (2021). *World economy set to lose up to 18% GDP from climate change if no action taken, reveals swiss re institute's stress test analysis*. https://www.swissre.com/media/press-release/nr-20210422-economics-of-climate-change-risks.html

WHO. (2021). Climate change and health. *World Health Organization*. https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health