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


WorldDynamics.jl: A Julia Package for Developing and Simulating Integrated Assessment Models

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Summary

WorldDynamics.jl is an open-source Julia package that provides a modern framework for developing, simulating, and investigating Integrated Assessment Models (in short, IAMs). IAMs are numerical models that estimate possible scenarios for the evolution of human society with respect to fundamental aspects such as capital investment, food production, natural resources, population size, and pollution, among others (Parker et al., 2002). The current version of the package implements the family of IAMs developed by the Club of Rome, which is a non-profit, informal organization of intellectuals and business leaders dedicated to the critical discussion of pressing global issues (Club of Rome, 1968). In particular, the library includes Forrester's World1 and World2 models (Forrester, 1970, 1973), the influential World3 model of Meadows et al (D. L. Meadows et al., 1974), and its 1994 and 2003 updated versions (D. H. Meadows et al., 2004). These models are typically structured into several sectors, which are, in turn, composed of several differential-algebraic systems of equations (in short, DAEs): this modular structure makes it easy to manipulate the sectors individually and to combine different DAEs into a unique model (see Figure 1, which represents the structure of the World3 model). The package benefits from Julia's scientific computing ecosystem, in particular from the efficient solver implementations for various differential equations provided by the DifferentialEquations.jl package (Rackauckas & Nie, 2017) and from the ability of the ModelingToolkit.jl package to compose differential-algebraic equations (Ma et al., 2021). WorldDynamics.jl provides also several support functions, which allowed us to convert the original systems of finite-difference equations into DAEs and to easily replicate all the plots included in the above-mentioned references (see, for example, Figure 2). It also allows the possibility of easily changing the parameter values and the systems of equations in order to simulate different scenarios. In other words, WorldDynamics.jl facilitates the use of advanced scientific computing approaches for both classical and new models.

Statement of need

Predicting the evolution of human society is a challenging and pressing question that science has always tried to address. The development of IAMs has been a major step in this direction, and more recently the use of computers has revolutionized the way these models are developed. The World3 model is considered one of the most influential computer simulations of the world-wide socio-economic system ever made. After it, many other models have been proposed, such as the DICE model (Nordhaus, 2018), originally proposed in 1992, and the most recent Earth4All model (Dixson-Declève et al., 2022; Randers & Collste, 2022). However, most of these models are implemented by using proprietary software, so that, even if the model specification is open source, it is not possible to verify how the model itself is simulated since the implementation of the DAE solvers and of the functions used in the model description

43 is not open source. Moreover, these software usually contain a limited set of solvers and, in
 44 general, they do not take advantage of modern approaches to scientific computing (Cavana
 45 et al., 2021). Therefore, our goal is to fulfill the need for a modern, open-source, flexible,
 46 and easy-to-use framework for IAMs that can be used to replicate and compare the results of
 47 existing models and to promote in-depth analysis of critical global issues, as well as a source
 48 of inspiration for the development of new models.

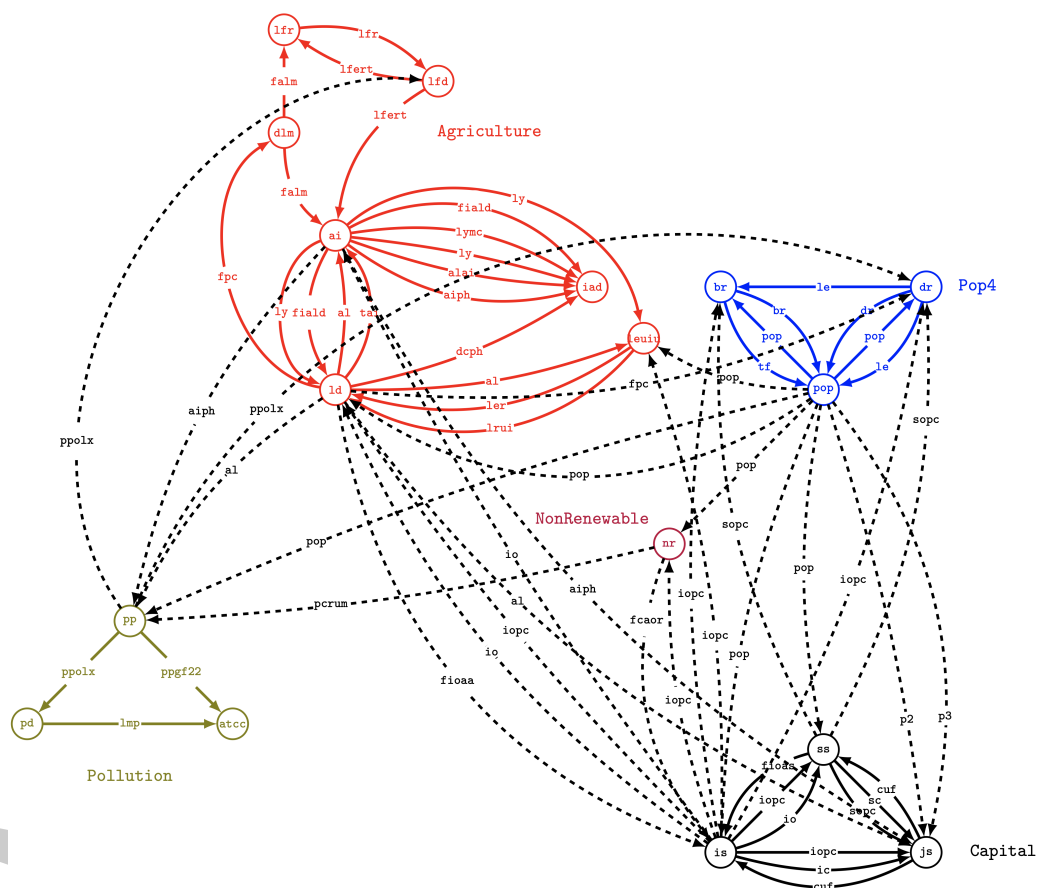


Figure 1: The World3 model (D. L. Meadows et al., 1974). The model contains 5 sectors: agriculture (red), population (blue), pollution (green), non-renewable resources (violet), and capital (black). Each circle denotes a DAE and each connection indicates that a variable (labeling the connection) is defined in a DAE (the tail circle) and used in another DAE (the head circle).

49 **Functionality**

50 WorldDynamics.jl comes with a tutorial which introduces the main functionalities of the
 51 package. In particular, the tutorial presents the following main features of WorldDynamics.jl.

- 52 ■ Replication of all the figures of the books describing the World1, World2, and World3
 53 models.
- 54 ■ Execution of sensitivity analysis by modifying initial values of variables.
- 55 ■ Analysis of alternative scenarios obtained by modifying the parameters of a model or
 56 the interpolation tables (used to approximate non-linear functions by means of linear
 57 segments).

- 58 ▪ Comparative analysis of performances and solutions obtained by different solvers.
- 59 ▪ Implement all the necessary modules required to create a new model using the framework.

Fig. 7.7

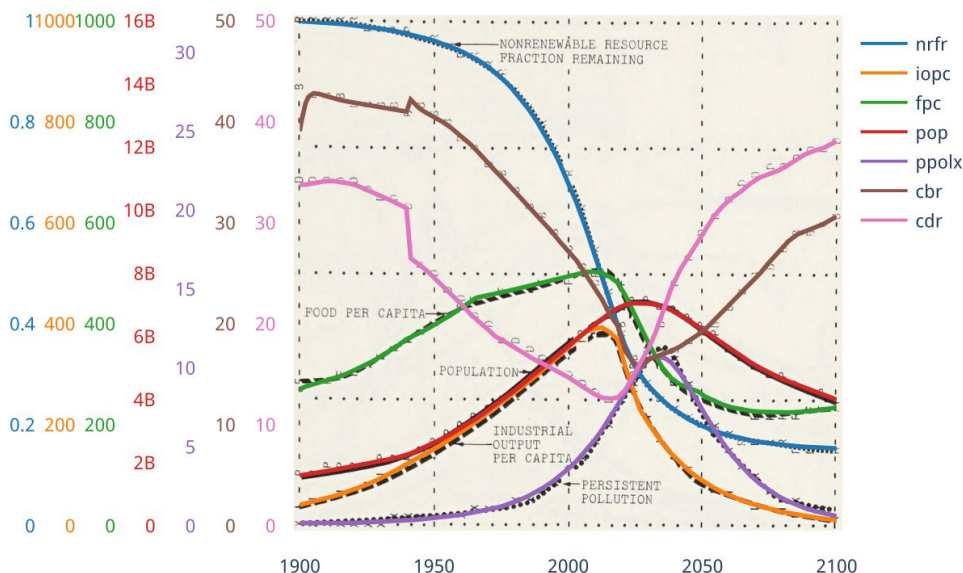


Figure 2: An example of the reproduction of a figure 7-7, World 3 reference run, included in (D. L. Meadows et al., 1974). The colored curves, which are generated by our package, have been superimposed on the original plots of the book (dotted, dashed, and one-character curves).

60 Related packages and implementations

61 Besides the official implementations on Vensim and Stella, which are two of the most popular system dynamics simulation environment, World2 and World3 have been repeatedly
 62 implemented in several different programming languages and simulation environments, such
 63 as Simulink and Modelica. Here, we mention some implementations of these models in
 64 three popular programming languages. In Python, there are several repositories whose code
 65 implements some of the IAMs proposed by the Club of Rome: in our opinion, the most
 66 complete description of the World2 and World3 models and of their implementation is given in
 67 (Vanwynsberghe, 2021). An implementation of World2 in R is described in (Mignan, 2020),
 68 while an implementation of the same model in C++ is given in (Hay, 2021). In the Julia
 69 ecosystem, there are some IAMs implemented using the Mimi framework `Mimi.jl`, such as the
 70 one included in `MimiPAGE2009.jl`, a package that implements a model for estimating the social
 71 cost of carbon emissions (Moore et al., 2018). `ClimateMARGO.jl` is an idealized framework for
 72 optimizing climate control strategies implementing the MARGO model (Drake et al., 2021).

74 Future work

75 The current version of the package could be enhanced in various ways. The package will be
 76 extended in order to include other more recent IAMs, such as the Earth4All model (Dixon-
 77 Declève et al., 2022). Moreover, a wide range of tools available in the Julia ecosystem
 78 could be used to improve the quality of the models, such as the addition of global sensitivity
 79 analysis algorithms (Dixit & Rackauckas, 2022), the use of data-driven differential equations to

80 automatically discover the models (Martensen et al., 2021), and optimizing parameter values
81 for some aspects of the models using the optimization package JuMP.jl (Lubin et al., 2023).

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