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 the human society with respect to fundamental aspects such as capital investment, food production, natural resources, population size, and pollution, among others (parker2002?). 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, Last visited Aprile 3, 2023). In particular, the library includes the Forrester's World1 and World2 models Forrester (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 by several differential-algebraic systems of equations (in short, DAEs): this modular structure makes easier 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 the 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), which have been originally proposed in 1992, and the most recent Earth4All model Randers & Collste (2022)), but most of them 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 all the functions used in the model description is not open source.

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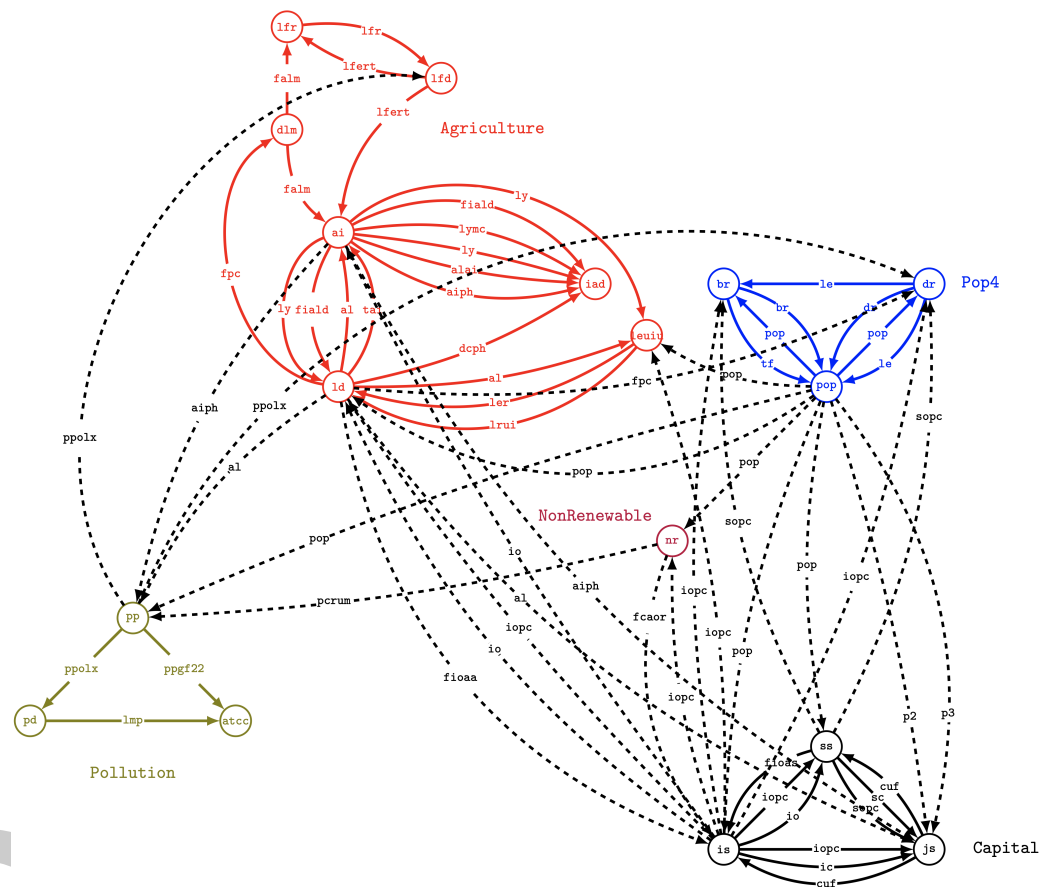48 new models.

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).

Functionality

50 WorldDynamics.jl comes with a tutorial which explains the main functionalities of the package.
51 In particular, the tutorial explains the following main feature of WorldDynamics.jl.

52 ▪ Replication of all the figures of the books describing the World1, World2, and World3
53   model.

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 ▪ Implementation of all modules necessary to integrate in the framework a new model.
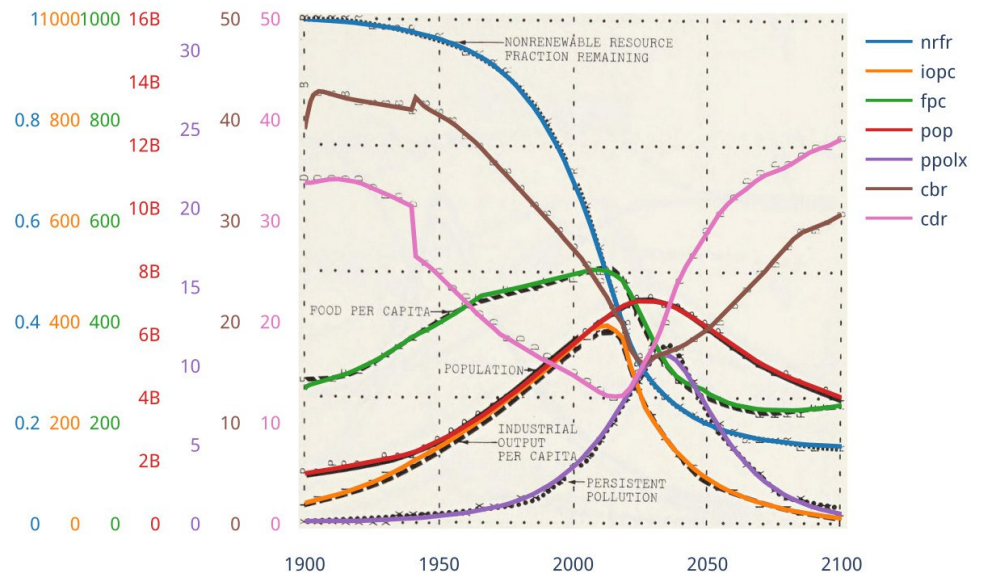
Fig. 7.7

Figure 2: An example of the reproduction of a figure included in (D. L. Meadows et al., 1974) (Figure 7-7, World3 reference run). 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).

Related packages and implementations

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

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 (Dixson-
77 Declève et al., 2022). A wide range of tools available in the Julia ecosystem could be used to
78 improve the quality of the models, such as the addition of global sensitivity analysis algorithms
79 (Dixit & Rackauckas, 2022), the use of data-driven differential equations to automatically

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

82 ## Acknowledgements

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