Research and Development of Co-simulation Technology for Attaining Inclusive Sustainability

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Abstract

To achieve inclusive sustainability, policies must be drafted and evaluated with an understanding of the interactions among the environment, economy, and society. To address this issue, NTT Human Informatics Laboratories is reproducing the environment, economy, and society on computers and using these simulations to evaluate policies. This article gives an overview of a co-simulation technology that will enable multiple simulation models to work together to achieve this goal. It also introduces prototyping of policy evaluation and discusses future prospects for this technology.

Keywords: co-simulation, sustainability, system of systems

1. Toward inclusive sustainability

The NTT Digital Twin Computing Research Center in NTT Human Informatics Laboratories has defined *inclusive sustainability* to mean sustainability that enables harmonization of the autonomy of the global environment, inclusive of the economic and social systems that are part of that environment [1]. To achieve inclusive sustainability, we seek to evaluate the effects of policy on the basis of an understanding of the complex interactions among the environment, economy, and society. However, it is difficult to understand all potential interactions by only observing the real world and difficult to evaluate such effects in the real world due to the cost of enacting them, time required for the effects to manifest, and fact that the effects may be irreversible. Therefore, we are investigating the modelling of environmental, economic, and social systems computationally and building a system that can be used to evaluate policies.

2. Developing co-simulation technology

Our approach to computer simulation of the environment, economy, and society follows the Digital Twin Computing (DTC) concept. Digital twin simulators of each phenomenon are created and combined in a simulation in an attempt to replicate reality. In an example described later in the article, a simulation of the water cycle in the natural environment is combined with simulations of human agricultural activity.

To adopt this approach, a technology to link individual simulators together is needed. We call this type of technology co-simulation technology. We have extracted requirements for co-simulation technology from our DTC White Paper [2], a survey paper on co-simulation [3], current specifications, such as FMI (Functional Mock-up Interface), HLA (High-Level Architecture), DCP (Distributed Co-simulation Protocol), and by prototyping use cases we have formulated. By selecting requirements from the following three perspectives, we aim to provide co-simulation technology that can be applied to various use cases with minimal revisions to software.

(1) Provision of basic co-simulation functionality
(2) Provision of functionality to analyze the speed and accuracy of computation
(3) Reusable models and data

The selected requirements are summarized in **Fig. 1** and described in detail as follows.

Requirements from perspective (1). A unified mechanism, called logical time, is needed to manage

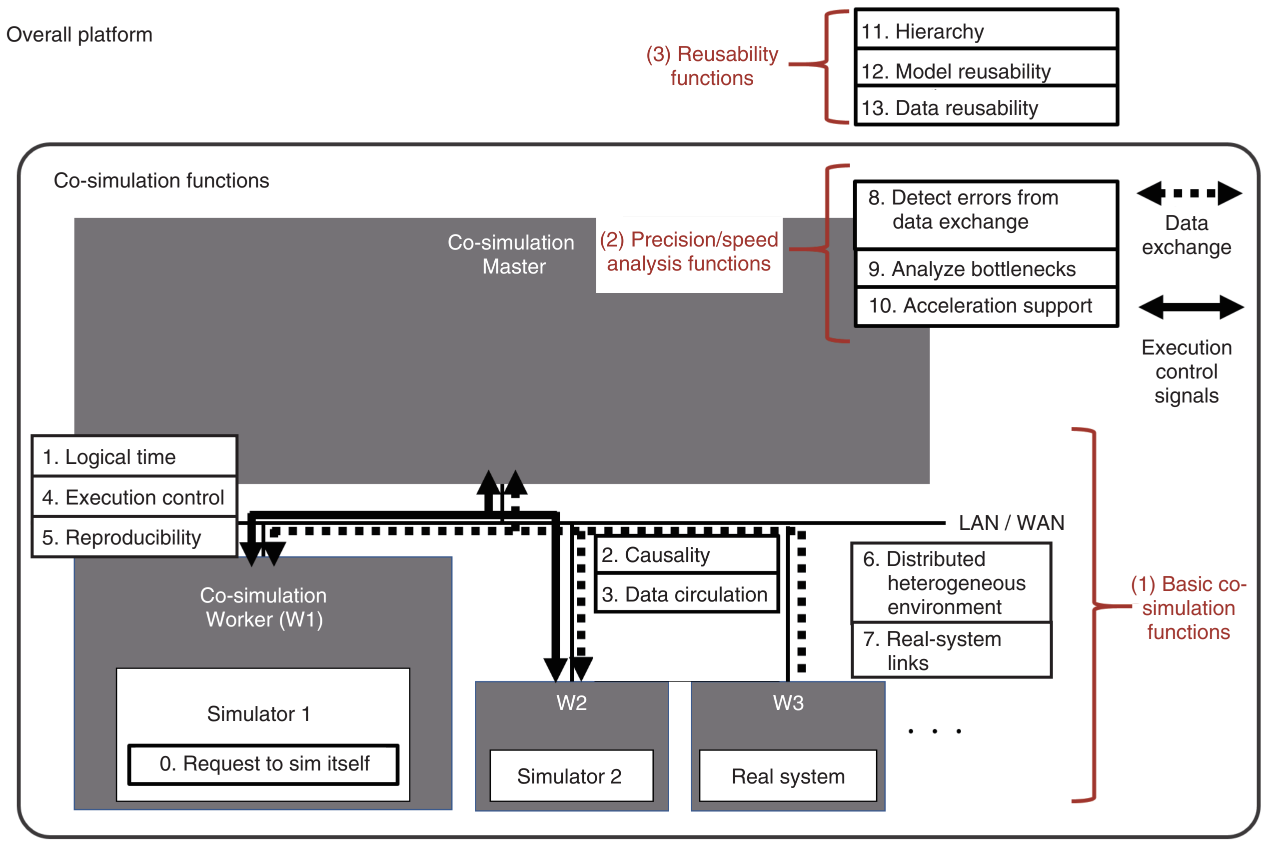


Fig. 1. Overview of co-simulation platform-technology requirements.

the internal time maintained independently within each simulator. There must also be a mechanism to exchange data among the simulators in accordance with the causality among simulator variables. This also requires management and control of the progress of each simulator in accordance with logical time so that such data exchange can occur at times appropriate for the simulators. Except for cases in which each simulator intentionally introduces a random disturbance, the computation results must be reproducible. This must be possible even if the various simulators are operating in separate environments distributed over a network. To further increase the range of application, real systems should be treated as simulators and participate in co-simulation.

Requirements from perspective (2). Regarding the accuracy and precision of computation, it is necessary to be able to detect any error that is introduced or magnified in the process of exchanging data and correct it. Speed of co-simulation greatly depends on the performance of simulators involved in co-simulation, so it will be necessary to provide easy-to-use functionality to analyze the computational bottleneck of each co-simulation architecture and accelerate processing, including use of surrogates.

Requirements from perspective (3). These requirements are directly related to having good user experiences on the platform. By enabling the re-use of the set of models and the connection models between them, they can be re-used easily in other co-simulation experiments, greatly reducing the time required to build co-simulations. They can also be used as a reference, which will be helpful when customizing a simulation. Providing reusable data and the information that should be used for which model enables the platform to be provided in a form that is easy to use, even for beginners. Ideally, we will provide reusable models and data in various repositories and data stores and expand them by accumulating real practical examples from users.

Figure 1 summarizes these requirements in a simple architecture. Perspectives (1), (2), and (3) have a total

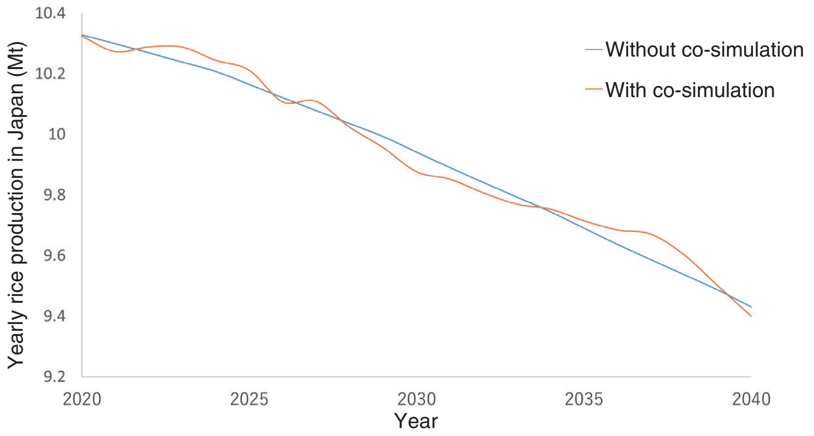


Fig. 2. Comparison of results with and without co-simulation (Yearly production of rice in Japan from 2020–2040).

of 13 requirements, which are mapped onto them.

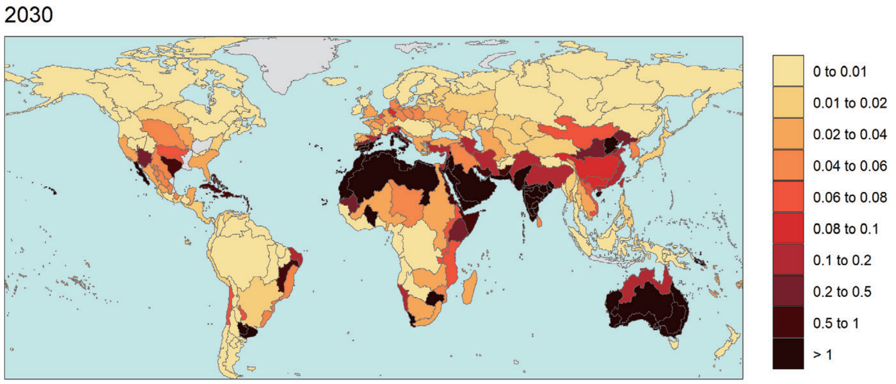
We developed software for providing the basic co-simulation functions (perspective 1) and using them in experiments. We describe an implementation method as follows, which is not the only implementation method. We assume a Master-Worker-type architecture, as shown in Fig. 1. Data between workers and simulators are exchanged using a format used by each simulator, such as accessing files or an application programming interface. The Master component manages the internal clocks of each simulator uniformly by mapping each worker to the logical time and issues instructions to workers so that the simulators run appropriately at the right times. Workers receiving these instructions, receive data intended for them from a data-exchange area (queue, etc.), carry out any required conversion, update any simulator state variable at the appropriate time, and conduct the indicated time-span of simulation. The simulation-execution time stamp is repartitioned as necessary and substituted or execution is processed. After conducting the simulation, the worker receives results to pass to other simulators, processes them, and sends them to the data-exchange area. This process is repeated until the entire co-simulation time has completed.

3. Co-simulation of environment, economy, and society and prototyping policy evaluation

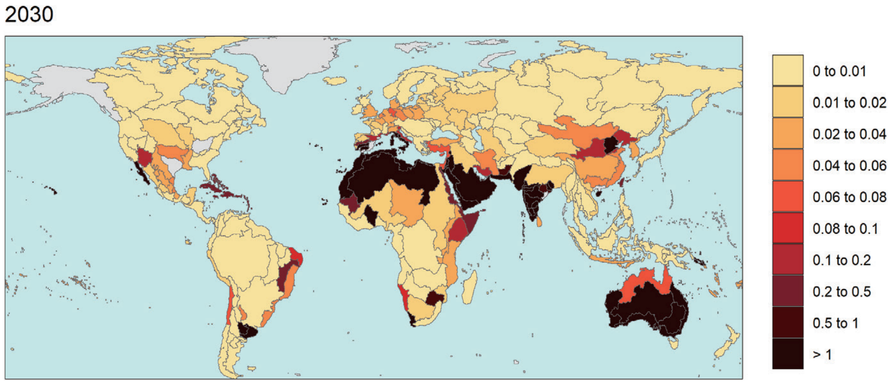
We are currently constructing a proof of concept (PoC) to realistically evaluate relationships between water cycles and food production under climate change. We are using the Integrated Land Simulator (ILS) [4] to compute approximately how much water is present at different locations on land. To compute food production, we are using the Global Change Analysis Model (GCAM) [5], which is a type of integrated evaluation model representing details of water use in the economy and society. This is the first attempt of this type of online co-simulation with detailed simulations of environmental and socio-economic conditions.

ILS computes data in 0.5-degree increments [01] of latitude and longitude with one-hour time stamps and outputs computed results as daily summaries. With the GCAM, however, geographical regions using water resources are (with some exceptions) defined in terms of polygon data for large-scale drainage basins (e.g. Japan is represented by a single drainage basin and one polygon), with time-stamps in units of years. The first task is to cover the gaps in space and time resolution between these two simulators. We took the average daily runoff values (approx. equal to available water) output by ILS, integrated spatially over drainage basins, then temporally over the whole year. This enabled us to substitute short-term data output over a grid for long-term data defined in terms of polygons.

Through this procedure, by substituting detailed surface-water amounts computed by ILS for available water amounts that can be used with the GCAM, we are able to observe the behavior of a socioeconomic model under realistic water-volume conditions. **Figure 2** shows the annual rice production figures for Japan from 2020 to 2040. The results differ between not using (blue) and using (orange) co-simulation, so the effects of data exchange in the co-simulation can be observed. Of course, the



(a) Water stress when water-consumption price is low



(b) Water stress when water-consumption price is high

Fig. 3. Policy evaluation prototyping (change in water stress due to setting of water-consumption price).

production values are not the same but remain within a close range, which suggests that simulator computations are proceeding appropriately. However, we found that there were problems with some of the results when we extended the period of the computation further. We attribute this to the fact that the socio-economic simulator is traditionally given results for a specific environment simulator and computes results on the basis of that assumption. Finding a solution for this is beyond the scope of this article, but this is the first problem identified through co-simulation, and we are currently studying ways to solve it.

Next, we present the results from using the co-simulation system for prototyping policy evaluation. We observed changes to global water stress when we changed the price of water consumption as an environmental policy. In this article, we define water stress as an index of the environmental burden due to water use. We evaluated it by comparing the demand for water (consumed amount) with the available amount of water.

Figure 3 shows a comparison of water stress when water consumption prices are set low and high. For simplicity, we set the same price for the whole world. Except in some areas, we observed that the overall water stress tends to be lower when the water price is high (Fig. 3(b)) than when it is low (Fig. 3(a)).

This indicates that, when simply considering water stress, setting a water-consumption price is an effective policy for lowering the environmental burden. However, this figure does not show the effects of increasing the price of water consumption on productivity and prices in agriculture and energy, so different evaluation methods are needed. We will select indices other than water stress by considering aspects such as well-being and evaluate their suitability for evaluating policy.

4. Conclusion and future prospects

We introduced an environment, economy, and society co-simulation PoC and conducted a one-way co-simulation of the effects of the environment on society and the economy. We are currently conducting co-simulation of the effects of society and the economy on the environment and plan to implement bidirectional co-simulation soon. The co-simulation of the environment, economy, and society we introduced has a global and macro scope, but we have also used our co-simulation technology to conduct local and micro environmental and social co-simulation. We conducted co-simulation with three simulators, i.e., for rivers, floodplains, and evacuee agents, to compute guidance for evacuees when floods occur.

In the discussion on the speed of the co-simulation technology, we mentioned the use of surrogates to increase speed. This has been a focus in the climate field and is currently attracting attention as a good match for modeling global demand. There are also requirements for user-friendly co-simulation that must be satisfied. We plan to continue developing our designs as we examine practical-usage scenarios and publish our results in the form of a co-simulation platform. We also plan to re-examine our ideal requirements according to our objectives, to address issues that arise with current society and economy simulators, and create appropriate designs in software. We also plan to summarize and publish these results.

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