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Development of a 1:1 scale Multi-region Agent-based Economic Model for Estimating Economic Impacts of Infrastructure Damages

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Abstract

We develop a 1:1 scale multi-region agent-based economic model (MR-ABEM), capable of simulating large national economies as a collection of regional/prefectural/state economies, for estimating the economic impacts of disasters. At the core, the MR-ABEM consists of several agent-based economic models (ABEMs), one for each region (e.g., a prefecture in case of Japan), which interact among themselves through exchange of labour and goods. Each regional economy is modelled at 1:1-scale and consists of thousands of firms belonging to hundreds of industries, thousands of foreign firms, millions of households comprising investors, workers, and inactive households, a bank, and the prefectural government. Parameters of regional-ABEMs are derived from the economic data of the represented prefectural economies. To simulate millions of economic entities, a high-performance computing extension is also implemented. The MR-ABEM has been calibrated and validated to the Japanese economy.

Keywords: agent-based economic model; multi-region economy simulation; high-performance computing; 1:1 scale simulation.

1 Introduction

Even though the damages caused by major natural disasters such as earthquakes are spatially localized, the interdependency of infrastructure and economic entities make the impacts propagate even beyond the national economy. To safeguard the economy and society against disaster risks, it is crucial to comprehend how the systemic risks propagate and to quantify these risks. This requires integrated simulation of infrastructure and economic systems at a fine scale including their interdependency.

For fine-grained integrated simulations, we need physic-based disaster simulators that can estimate the disaster-induced damages sustained by each infrastructure component and an economy simulator which can include all major economic entities, their interactions, and the interdependence of economic entities and infrastructure components. There has been a significant progress in the development of high-resolution physics-based disaster simulators [1, 2, 3]. In order to utilize high-resolution results obtained from the physics-based disaster simulators, we need an economy simulator that can simulate the behaviour of each economic entity and its dependence on infrastructure components.

Traditionally, two types of economic models, namely computable general equilibrium (CGEM) and input-output (IO) models, have been used to simulate post-disaster economies to estimate the economic impact of disasters. Some of the well-known CGEM are developed by Rose and Leo [4], Brozovic et al. [5], and Tatano and Tsuchiya [6]. The problem with the CGEMs is that these models are based on neo-classical assumptions i.e., the economic entities are perfectly rational, perfectly informed, and make decisions to maximize their utilities. Post-disaster conditions are quite far from these ideal assumptions as the economy is in transition state and the agents don't have full information of the market. IO model developed by Santos [7], Hallegatte [8], and Henriet et al. [9] are some of the earliest IO models applied to estimate the economic impacts of disasters. IO models utilise the IO table to model the interdependency of the industrial sectors and final demand sectors. Both CGEM and IO models are highly coarse-grained since only a few representative economic entities are considered instead of the millions in the real-world. Because of the coarseness, it is not possible to include different levels of damages sustained by various infrastructure components and their owners. Inclusion of fine-grained damage details is very important for measuring their impacts on the economy because of different levels of resilience and capacity of the damaged infrastructure owners.

Another class of economic models is agent-based economic models (ABEMs) which simulate economy as a dynamic system of interacting heterogenous and independent agents. The agents of an ABEM don't follow neoclassical assumptions. Their behaviour is modelled using heuristic rules derived from historical economic data of the represented real-world economic entities. The ABEM can simulate any economy at 1:1 scale given the data availability. According to our literature survey, the ABEM developed by Poledna et al. [10] is one of the most complete ABEM that can simulate a national economy at 1:1 scale. The model has been validated to the Austrian economy and used to analyse the impacts of flood disaster on the Austrian economy [11]. It is easier to integrate it with spatially distributed infrastructure components for modelling the dependency of economic entities and infrastructure. Hence, an ABEM is an ideal tool for simulating postdisaster economy for estimating economic impacts of disasters.

In our previous research [12, 13], we developed a 1:1 scale HPC-enhanced ABEM for the Japanese economy and integrated it with buildings. The integrated model was used to analyse the impacts of each damaged building on the Japanese economy. Even though the ABEM [12, 13] is 1:1 scale, it is calibrated using the national macroeconomic data. Therefore, the agents across the nation have homogeneous behaviour. For example, propensity to consume for all workers is same. As we know, the needs and behaviours of economic entities such as consumers can widely vary according to geographical location. These geographical variations can be approximated as a collection of regional economies within which economic entities of a given type have homogeneous behaviour. To include the regional heterogeneity of a national economy, we extend the ABEM to a multi-region ABEM (MR-ABEM). The MR-ABEM has been calibrated and validated to the Japanese economy. Publicly available micro and macro-economic data of the prefectural economies and the national economy are used to derive model parameters. Validation tests show a good agreement in the simulated and observed values of real and nominal production, and other economic parameters.

To use the MR-ABEM for simulating postdisaster economies, it needs to be integrated with infrastructure networks, and physics-based disaster simulators. It has already been integrated with buildings. We are currently working on the development of an infra-network simulator and its integration with the MR-ABEM. In this article, we present the details of MR-ABEM and its validation to the Japanese economy.

The rest of this article is organized as follows. Section 2 explains the MR-ABEM in detail. The calibration and validation of the MR-ABEM are discussed in Section 3. Section 4 presents our current and future works. Section 5 concludes.

2 Model Description

The structure of the MR-ABEM is inspired by the real-world structure of a national economy which consists of several regional economies. The MR-ABEM simulates a national economy as a collection of regional economies considering their heterogeneity. A region might represent a state, a prefecture, or a group of prefectures. For example, the Japanese economy can be considered as consisting of 47 prefectural economies or 9 regional economies (Kanto, Tohoku, Shikoku, etc.) depending on the desired level of granularity. The MR-ABEM consists of several ABEMs, one for each regional economy, which interact with each other through exchange of labour, goods and services. This section provides details of the base ABEM and the integration of the ABEMs into the MR-ABEM.

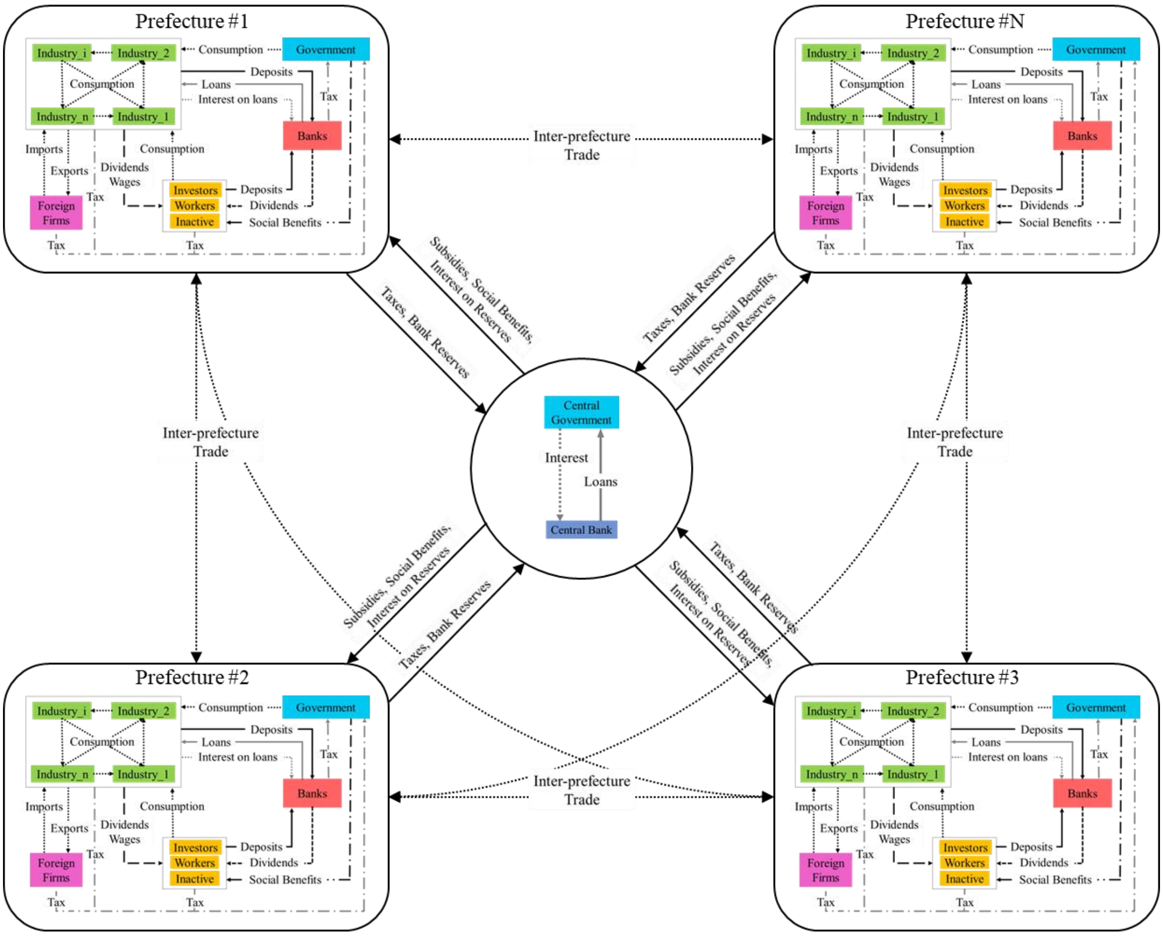


Figure 1. Schematic diagram of the multi-region agent-based economic model (MR-ABEM).

2.1 Agent-based economic models

An ABEM simulates an economy as a dynamic system of interacting heterogeneous and independent agents which represent real-world economic entities. A schematic diagram of a typical ABEM is shown in Figure 1. Schematic diagram of the multi-region agent-based economic model (MR-ABEM). within round cornered rectangles. A typical ABEM consists of all major economic entities and models their interactions. The base ABEM used for this study is developed by Poledna et al. [10]. The agent types and their actions are explained below.

2.1.1 Firm agents

The firm-agents represent domestic firms that produce goods and services utilizing labour, capital and input goods. Depending on the type of products, the firm-agents are categorized into 108 industrial sectors as per standard industrial classification used in Japan. The capital goods required for production are assumed to be same for all firm agents irrespective of their industry whereas input goods depend on the industry of the firm agents. At the beginning of each simulation period, firms decide their production quantity and unit price of products. After that, the firms check their labour requirements and fire extra workers or fire new workers in the labour market. Next, depending on the available labour, input goods, and capital goods, the firms revise their production estimates and start production. To replenish the stock of input and capital goods required for future production, the firm estimate their budgets for input and capital goods. A financially constrained firm may apply for a loan to the bank.

After carrying out production, the firm-agents enter goods market to sell their products and buy necessary input and capital goods. The firm-agents pay wages to their workers, dividend to their investors, loan instalment and interest on loans to the bank, taxes on their production, corporate tax, and the employers' contribution of social insurance for their workers to the government. In the end of the period, the firms do financial accounting and calculates their net profit, dividend to be paid, interests to be paid, equity etc. If the bank deposit and equity of a firm falls below zero, it goes bankrupt. The bankrupt firm is revived by the bank by writing off a portion of the loan and overdraft. The revived firm inherits all assets but a portion of the loan of the bankrupt firm.

2.1.2 Household agents

Households are divided into three categories namely investors, workers, and inactive households.

Investors represent the owners of the firms and banks. Currently, the model considers only one investor per firm and bank. However, it can be extended to include multiple investors to mimic the reality given the data availability. The main source of investors' income is the dividends on their investments.

Workers provide labour to the firms and receive wages. In each period, unemployed workers look for jobs in the job market by visiting a random set of firms with vacancies. Workers are not categorized according to their skills or specialties. Irrespective of the job type and wages offered, the workers accept the first job they find.

Inactive households represent the remaining population. Government subsidies are their main source of income.

Each period, the households decide their budget for consumption goods and investment goods based on their expected income. In the goods market, the households buy required goods. If they cannot buy all they need, unspent budget is saved involuntarily. All households pay consumption tax to the government whereas only investors and employed workers pay income tax and social security contributions to the government.

2.1.3 Bank agents

Due to the absence of reliable data for multiple banks, only one bank is assumed in the economy. The bank accepts deposits from firms and households and pays interest on the deposit. The customers can request overdrafts and loans from the bank. The interest on overdrafts and loans is the source of income for the bank. The bank keeps its deposits as reserves at the central bank or receives advances from the central bank according to monetary policy. The bank pays dividends to its investor, corporate tax to the government.

2.1.4 Government

The government serves two functions: as a consumer in the market, and a redistributive entity that levies various taxes and collects social contributions to provide social benefits to the households or subsidies to the firms. The government is composed of various government entities which represent local governments, municipalities, etc. Consumption budget of the government for the product of an industry is given exogenously in each simulation period. To meet its fiscal deficit, the government takes loans from the central bank.

2.1.5 Central bank

The central bank sets policy rate. It provides liquidity to the banking system by extending advances to the bank and takes deposits from the bank in the form of bank reserves. Central bank is the main creditor to the central government and extends loans to the government unconditionally.

All the above-mentioned actions of the agents are modeled using well-defined mathematical rules which are provided in detail in the reference [10, 12]. In order to save space and avoid repetitions, we refer interested readers to the original articles.

2.2 Integration of the ABEMs into an MR-ABEM

As discussed earlier, each regional-ABEM simulates the economy of one prefecture or region. All prefectural ABEMs are integrated into an MR-ABEM as shown in Figure 1. Schematic diagram of the multi-region agent-based economic model (MR-ABEM).. The regional ABEMs interact with each other by exchanging labour and goods and services. On the top, there is a central government which collects national taxes and provides subsidies to firms and households of the prefectures in addition to setting fiscal policy for the national economy. The regional government interacts with the national government to meet out its fiscal deficit and to receive regional grants as applicable. Furthermore, the central bank controls the monetary policy for the whole economy and provides loans to the central government. In addition, the central bank calculates and publishes various economic indices such as capital formation price index, consumer price index, inflation and growth rates of different regions, which the agents of corresponding regions use for decision making.

Agents of each region are initialized according to the regional economic data. The agents are assigned a geographical location, prefecture ID, and their regional ID to model spatial distribution of economic entities.

2.3 Computer implementation

The MR-ABEM is implemented in C++ using object-oriented programming to manage the data and functions of each agent independently. In addition, a distributed-memory parallel implementation of the model has been developed to realize 1:1 scale simulation of large economies having hundreds of millions of agents [1]. As an example, there are 130 million agents in a 1:1 scale model of the Japanese economy.

3 Calibration and validation

The MR-ABEM is calibrated to the Japanese economy of 2015 at 1:1 scale using publicly available micro and macroeconomic data of the national economy and prefectural economies of Japan. Using generated parameters, the Japanese economy is simulated for 3 years (2015-2018) and the simulated values were compared with the observed data for validating the model. This section presents data sources, a short overview of parameter generation, and the validation.

3.1 Data sources

Ideally, economic data of each economic entity is required to derive the parameters of its representative agent. However, due to the lack of such data, macroeconomic data of prefectural economies and various economic surveys conducted by the Japanese government are used to derive agents' parameters by disaggregating the macroeconomic data such that the distributional properties observed in the microeconomic data are preserved. As an example, it is a well-known fact that the firms size distribution follows a power law therefore, the macroeconomic data of each industry is disaggregated in such a way that the disaggregated data follows the power law. Table 1. Economic datasets and their sourceslists main datasets used and their sources.

3.2 Model parameters generation

The model parameters can be divided into two categories: parameters private to each agent, and parameters shared by all agents of a particular class. As an example, income of a household is unique to the household whereas propensity to consume is assumed to be the same for all households of a prefecture.

Input-Output tables (IO tables) of the prefectures are the main datasets for deriving shared parameters of the regional-ABEMs because the IO tables contain interdependent relationships among industrial sectors, households and government entities. Furthermore, sector-wise wage rate, productivities of labour, input and capital goods consumed, tax rate on products and production, imports, and exports are also included. In Japan, IO tables are published every 5 years, with the 2020 IO table being the most recent one. We calibrated the regional-ABEMs to first quarter of 2015 using the 2015 IO tables because we need sufficient observed data for model validation. We refer interested readers to Gill et al. [12, 13] for details of the data generation process for prefectural ABEMs. In the 1:1 scale model of the Japanese economy, there are approximately 130 million agents comprising 5.3 million domestic firms belonging to 108 industrial sectors, 5.3 million investors, 61.2 million workers, 60.5 million inactive households, 2.6 million foreign firms, 1.3 million government entities, one bank for each prefecture and the central bank.

Table 1. Economic datasets and their sources

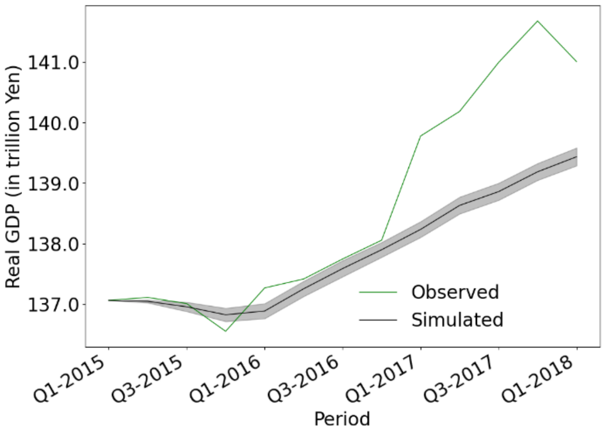
Source	Dataset
Prefectural government websites, such as https://www.pref.aichi.jp/soshiki/toukei/io2015.html#20220214109 for Aichi.	Input-Output table (IO table) of each prefecture.
Official Statistics of Japan (https://www.e-stat.go.jp)	Enterprises employees census. Population census. Workplace census. Household consumption survey. GDP time-series data. General government accounts.
The Cabinet Office, the Government of Japan	System of national accounts. Household income, expenditure and savings. Capital stocks.
Bank of Japan	Sectoral balance sheet. Policy rate. Industrial production price index time series.

3.3 Validation

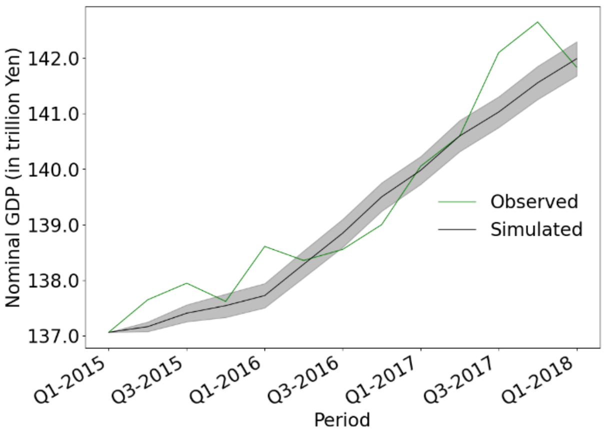
Model validation is an important step in numerical simulations to check that the developed model is capable of reproducing the target system to a sufficient accuracy. For validating the MR-ABEM, we simulate the Japanese economy under normal economic scenario and compare the simulation results with the observed economic indices. Following is the model settings employed for the validation tests.

1. Initial parameters of the agents and model parameters of the prefectural ABEMs are generated from the Japanese economy data for 1st quarter 2015.
2. One simulation period represents one financial quarter.
3. Simulations are conducted for 13 periods starting from Q1 2015 to Q1 2018.
4. Apart from quarterly exports, imports, and government consumption for the simulated quarters, no external data or inputs are given to the model during simulation.
5. To incorporate various uncertainties in the data generation process, Monet Carlo simulations with 100 samples are conducted.

Ideally, the MR-ABEM should be validated by verifying the performance of prefectural economies. At the current development stage, the model is validated at national economy level only even though the simulated values of prefectural economic indices are available. Out of various available economic parameters, we present a comparison of simulated and observed values of real and nominal GDP of Japan since these indices include the influence of both supply and demand-side decisions of the agents of all prefectures. Figure 2. Comparison of observed and simulated values of quarterly real and nominal GDP of Japan presents a comparison of observed and simulated values of quarterly real GDP and nominal GDP. The light gray region represents $\pm 2\sigma$ uncertainty margin. As shown in the Figure 2. Comparison of observed and simulated values of quarterly real and nominal GDP of Japan, the simulation results are in a good agreement with the observed data for up to Q4 2016. However, Q1 2017 onwards, the model underestimates the real GDP. The maximum error is around 2%. The reason for this underestimation is lower growth rate in the simulated economy. On the other hand, nominal GDP is very well reproduced as shown in Figure 2. Comparison of observed and simulated values of quarterly real and nominal GDP of Japan. Since nominal GDP includes the influence of both growth and inflation rates, the model seems to underestimate growth rate and overestimate inflation rate for a period of Q1 2017 to Q1 2018. Nevertheless, the simulation error is only 2% which is significantly small for this kind of problems. The error can be reduced by improving the simulation accuracy at prefecture level, which is an ongoing work.



2a. Real GDP



2b. Nominal GDP

Figure 2. Comparison of observed and simulated values of quarterly real and nominal GDP of Japan

4 Present and future works

The ultimate goal of this research is to develop a 1:1 scale integrated infrastructure and economy simulator that can consider the interdependency of infrastructure and economic entities. Such a simulator can include spatial distribution of infrastructure and different levels of damage suffered by various infrastructure components and their owners (economic entities), which is necessary for reliable estimates of economic impacts of disasters.

In this paper, we presented a 1:1 scale MR-ABEM that can simulate a national economy as a collection of regional economies considering the heterogeneous nature of regional economic entities and the interdependence of economic entities of different regions. We calibrated it to the Japanese economy using micro and macro economic data of the Japanese economy. Our validation tests show that it can simulate the Japanese economy with an acceptable accuracy. The development of a 1:1 scale MR-ABEM is an important milestone towards the realisation of the long-term goal of this research..

The next step is to integrate the MR-ABEM with spatially distributed infrastructure components. Notably, it is straightforward to integrate the MR-ABEM with buildings since each building can be assigned to the agents depending on location and occupancy type of the building and the floor area occupied by the agents.

The next challenge is to develop an infra-network simulator for modeling transportation, energy, and water networks. We are currently working on the development of the infra-network simulator and its integration with the MR-ABEM. Once fully developed, the integrated simulator will be used to perform end-to-end simulations of disasters and economy at 1:1 scale. We hope that the simulator will be help us to understand how the disaster impacts propagate from infrastructure to the economy. Further, it could be used for making efficient disaster risk-reduction policies and recovery plans for quick and equitable recovery from a disaster.

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