ESTIMATION OF POST-DISASTER CO_2-EMISSIONS USING INTEGRATED SIMULATIONS OF DISASTERS AND ECONOMY

災害・経済のシミュレーションを用いた災害後の CO_2 排出量の推定

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地震災害と経済の統合シミュレーションを利用した，災害後の復興における CO_2 排出量を推定する方法論を提示する。本手法を用いて，阪神地域におけるシナリオ南海トラフ地震発生後の CO_2 排出量を推計した。この地域に建つ住宅，学校，病院，商業施設，小売店などからなる 180 万棟の建物に与える影響が考慮されている。震災後 5 年間の産業別 CO_2 排出量を推計した結果，復興期における産業別 CO_2 排出量が増加することが分かった。非災害時のシナリオと比較すると，5 年間で 9,770 万トンの CO_2 が追加で排出されると推計され，これは日本の年間排出量の約 9%に相当する。

キーワード： CO2 排出量，地震災害，エージェントベース経済シミュレーション，統合地震シミュレータ，サステナビリティ

We present a fine-grained integrated methodology that utilizes end-to-end simulations of earthquake disasters and economy to estimate the CO_2-emissions during the post-disaster recovery. Using the methodology, we estimate the quantity of CO_2-emissions in the aftermath of a scenario Nankai Trough earthquake in the Hanshin industrial zone of Japan. Impact of the earthquake disaster on all 1.8 million buildings, comprising residential towers, schools, hospitals, commercial offices, retail stores, etc., in the region is evaluated. Industry-wise CO_2-emissions during the post-disaster recovery are estimated for 5 years after the disaster. Compared to the non-disaster scenario, 97.7 million ton more CO_2 is expected to be emitted over the course of 5 years, which is approximately 9% of annual emissions in Japan.

Key Words: CO2-Emissions, Earthquake Disaster, Agent-based Economic Simulations, Integrated Earthquake Simulator, Sustainability

1. INTRODUCTION

As we are witnessing the adverse impacts of global warming, there is no doubt that it poses an existential threat to humanity if not tackled in time. Slowing down global warming requires substantial reduction in the emissions of CO_2 and various other green-house gases (GHGs) that are emitted due to various economic activities. As an example, the construction sector accounts for nearly 13% of total CO_2-emissions worldwide. Since economic activities are indispensable for the well-being of society, sustainable development is the key to curb emissions. Natural disasters, including those caused by global warming, destroy multi-billion worth of infrastructure every year, which must be rebuilt/repaired. Post-disaster reconstruction activities can emit significant amounts of CO_2 hampering our progress towards net-zero emissions. A thorough understanding of disaster impacts is necessary to make effective policies to minimize these impacts. To this end, we are developing a large-scale fine-grained integrated simulation technology that can estimate the impacts of disasters on economy and infrastructure by simulating all major economic activities and their dependency on infrastructure. In this report, we introduce our simulation technology and to demonstrate its application, we estimate the CO_2-emissions caused by a potential Nankai Trough earthquake.

We use a High-Performance Computing (HPC) enhanced agent-based economic model (ABEM)[1] to simulate the Japanese economy at 1:1 scale and an Integrated Earthquake Simulator (IES) [2] to simulate the impacts of disaster on each building located in the affected region. 1:1 scale simulation with ABEM[1,3] implies the simulation of national economy considering the economic activities of each individual economic entity such as each of the firms in various industries, each household, general government, and the banks. Macroeconomic data is utilized to derive the individual entity's economic data which is then used for calibration of the ABEM[3]. The extent of damage and damaged states of the infrastructure obtained from the IES are fed to the ABEM to simulate the post-disaster economic activities and the associated CO_2-emissions are calculated. For this study, we assume that the disaster occurs in the first quarter of 2015. The earthquake disaster and the damage to 1.8 million buildings in Osaka, Kobe, and Awaji Island are estimated using the IES[2] and the PACT[4]. The estimated damages are assigned to the building owners and the post-disaster economy is simulated at 1:1 scale using the ABEM for 5 years after the disaster. A comparison of the emissions under normal scenario and the disaster scenario is presented.

The rest of this report is organized as follows. Section 2 explains the methodology in detail. Model calibration and data generation process is discussed in section 3. Simulation results are presented in section 4. Section 5 concludes.

2. METHODOLOGY

CO_2-emissions due to various industrial sectors of an economy are directly proportional to the scale of production. Utilizing the fuel consumption data of each industry, industry-wise CO_2-emission coefficients (quantity of CO_2 emitted per million Yen worth of production) can be obtained. We estimate post-disaster CO_2-emissions using CO_2-emission coefficients and post-disaster industrial production quantities.

To estimate the post-disaster production levels, a three-step sequential process is used to perform high-resolution end-to-end simulations of earthquake disasters and economy for estimating the impacts of disasters. The first step is to simulate the disaster and its impact on infrastructure using physics-based disaster simulators; in the second step, infrastructure response is converted to damages, required repair cost, and repair time. The damaged states of the infrastructure and repair cost and time are then used in an economic model to simulate the post-disaster economy. The focus of the current study is an earthquake disaster therefore, we provide a detailed explanation of the methodology for estimating the impacts of an earthquake disaster.

2.1 CO_2-EMISSION COEFFICIENTS

Industrial CO_2-emission coefficients (quantity of CO_2 emitted per million Yen worth of production) are obtained using the Input-Output analysis[5]. The Input-Output analysis requires the Input-Output (IO) table of the economy and fuel consumption data of each industry. CO_2 emitted due to the consumption of fuel is termed as direct CO_2-emission. Direct CO_2-emission is obtained by multiplying the quantities of fuels consumed with the CO_2-emission coefficient of the fuel. Total CO_2-emission in an industrial sector is the sum of direct emission, and indirect emission caused in other industrial sectors that produce intermediate goods necessary to carry out production in the sector. Let **d** and **e** be the vectors of direct emission coefficients and total emission coefficients of the industries. The relationship between **d** and **e**, as obtained from the Input-Output analysis, is given in Equation 1.

$$\mathbf{e} = \mathbf{d}\{\mathbf{I} - (\mathbf{I} - \mathbf{M})\mathbf{A}\}^{-1} \quad (1)$$

where **I** is the identity matrix, **A** is the input coefficient matrix, and **M** is the import coefficient matrix. Utilizing vectors **d** and **e** and industrial production quantities, direct and total emissions attributable to the sectors are calculated.

2.2 SIMULATION OF SEISMIC RESPONSE OF THE INFRASTRUCTURE

The response of the infrastructure to the seismic wave is simulated using a large-scale Integrated Earthquake Simulator (IES)[2]. Given a seismic wave, the IES provides seismic response parameters like inter-story drifts, floor accelerations, floor velocities, residual drifts, of the simulated infrastructure.

2.3 ESTIMATION OF DAMAGES AND REPAIR COSTS

Seismic response of the infrastructure components is not sufficient to estimate the economic losses. It should be converted to the amount of damage sustained by the infrastructure, which is useful for the estimation of economic impacts of the disaster. We use Performance

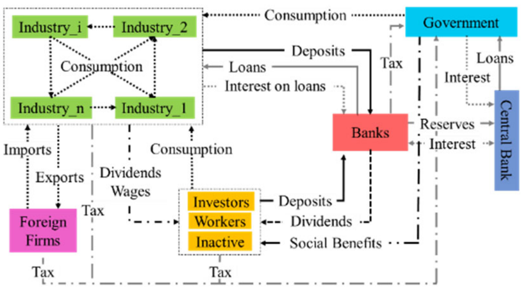


Fig. 1. Schematic diagram of the agent-based economic model (ABEM)

Assessment Calculation Tool (PACT)[4] to convert the seismic response of buildings into required repair or reconstruction cost. PACT is developed by Federal Emergency Management Agency (FEMA); it utilizes a vast database of fragility and consequence functions of various building components. It also includes a normative quantity estimation tool which can be used to estimate non-structural components of buildings based on their size and occupancy types. Feeding the seismic response of buildings obtained from the IES into PACT, we obtain repair costs required for restoring the buildings to their pre-disaster state.

2.4 SIMULATION OF POST-DISASTER ECONOMY

The repair costs obtained from PACT are used in an economy simulator to simulate the post-disaster economy and estimate the impacts of the disasters. For fine-grained simulations of the economy, we are using an improved version of an agent-based economic model (ABEM)[6]. This section explains the ABEM in detail.

2.4.1 AGENT-BASED ECONOMIC MODEL

Fig. 1 presents a schematic diagram of the ABEM. It contains millions of agents representing real-world economic entities such as firms of various industrial sectors, workers, banks. The agents mimic all major actions of their real-world counterparts. The rules defining the agents' interactions are derived from the behavioral economics or the observed economic data of the represented agents. Characteristics and actions of all agents are presented below.

(1) Firms: Firms are grouped into several industries depending on their product. All firms of an industry produce similar products and follow similar behavior rules. However, the firms differ in terms of the scale of production, price of products, owned capital, deposits, etc. The firms need intermediate goods, capital goods, and labor to produce. It is assumed that there is only one type of capital good in the economy. However, productivity of capital is different for firms of different industries. Intermediate goods required by firms of different industries are different. At the start of each simulation period, the firms decide the quantity to produce and price of their products based on their expectation of growth and inflation rates as well as their experience. After deciding the production quantity, the firms either hire or fire workers to meet their labor requirement. The firms utilize their stock of capital and intermediate goods available at the start of each period. The firms' production may be limited by the unavailability of sufficient resources. Next, the firms decide their consumption and investment budget considering capital depreciation and the intermediate goods used in production in the current period. If the firms have shortage of funds, they apply for loans. Depending on their financial health, their loan application may be rejected which will limit their investment plans.

After all the firms have carried out production, they enter the goods market as suppliers and buyers of various goods and services. In the goods market, all sellers are available to all buyers and the buyers prefer bigger sellers with lower prices to buy products. Depending on the demand and supply, some firms may be left with unsold goods and may be unable to buy everything they need.

The firms pay wages to their workers, repay a portion of loan to the bank and the interest on loans, pay various taxes, such as tax on production, corporate tax, and the employers' contribution of social insurance for their workers, to the government. They also pay dividends to their owner.

In addition, there are foreign firms in each industry which act as exporters or importers. The quantity to export and import is given exogenously to the model.

(2) Households: Households consist of investors who are firm owners, workers who supply labor to the firms, and inactive households who represent the non-working population. The dividend paid by the firms is the source of income of investors. The

workers receive wages for the labor supplied to the firms. The inactive households rely on social benefits from the government. Additionally, all the households receive some kind of social benefit from the government. The households spend a portion of their income on consumption and investment goods. If they are unable to buy all they want, they will save the remaining amount. Further, they pay income tax, value added tax, and social security contributions to the government.

(3) Bank: Due to absence of reliable data for multiple banks, only one bank is considered. The bank keeps deposits of firms and households and pays interest on the deposits or receives interest on overdrafts. It also provides loans to firms. The bank keeps its reserves at the central bank or receives advances from the central bank. The bank pays dividends to its investor and pays corporate tax to the government.

(4) Central Bank: The central bank sets the 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.

(5) Government: The government acts as a consumer in the market, and a redistributive entity that levies various taxes and social contributions to provide social benefits to the households or subsidies to the firms. The government consists of various government entities which represent central governments, local governments, and social security funds. The consumption budget of the government is given exogenously to the model and is assumed to be constant in real terms but adjusted to the last period's average price of the product of the industry.

To simulate the post-disaster economy, the damages to the buildings are assigned to the buildings' owners i.e., firm or household agents. Damage to industrial buildings (e.g., factories, offices) represents capital loss to the firms. Because of the capital loss, the post-disaster production level of the firms will be lower than the pre-disaster level. To attain the pre-disaster level of production, the firm agents plan new investments to recover the damaged capital in the post-disaster periods. On the other hand, the households whose homes were damaged can't lead a comfortable life. From an economic point of view, some of the impacted households may not be able to go to work while some others can work but only part-time. This will cause labor shortage in the impacted region hindering the post-disaster recovery. Moreover, the income of the impacted households will fall making it difficult for them to invest in recovery. Households may use insurance claims, bank deposits, or government aid for recovery. Post-disaster decision-making and the resulting economic dynamics are simulated using our HPC-enhanced ABEM.

3. INPUT DATA GENERATION

3.1 DATA SOURCES

3.1.1 CO_2-EMISSION COEFFICIENTS

Industrial fuel consumption data, required to derive industrial CO_2-emission coefficients, is sourced from Embodied Energy Emission Intensity Data provided by the National Institute for Environmental Studies, Japan (https://www.cger.nies.go.jp/publications/report/d031/jpn/datafile/embodied/2015/390.html). The latest available data is for the year 2015 therefore, the first simulation period is set to first quarter of 2015.

3.1.2 ABEM PARAMETERS

The ABEM is calibrated to the first quarter of 2015 of the Japanese economy. The main dataset used to derive the ABEM parameters is the 2015 IO-table at producer price for Japan since it contains the interdependencies among economic entities. In addition, individual agent's data is obtained by disaggregating the macroeconomic data since data at such a fine scale is unavailable. To derive the agent-level data, various datasets such as business census, system of national accounts, history of industrial production, households' income and expenditure survey data, general government accounts, etc., are used. The datasets are obtained from RIETI (https://www.rieti.go.jp), e-Stat (https://www.e-stat.go.jp), and the Cabinet Office (https://www.esri.cao.go.jp). Because of the limited space, the details of the data generation process are skipped. The interested reader is requested to refer to Gill et al.[3] for the details.

In the generated 1:1 scale model of the Japanese economy, there are a total of 130 million agents consisting of 1.8 million domestic firms, 0.9 million foreign firms, 1.8

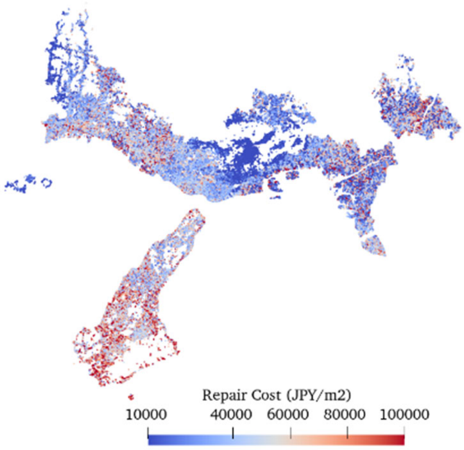


Fig. 2. Repair cost in Japanese Yen per unit floor area for the simulated buildings

million investors, 68.9 million workers, 56.4 million inactive households, 0.5 million government entities, one bank, a central bank, and the general government.

3.1.3 BUILDINGS AND EARTHQUAKE SCENARIO DATA

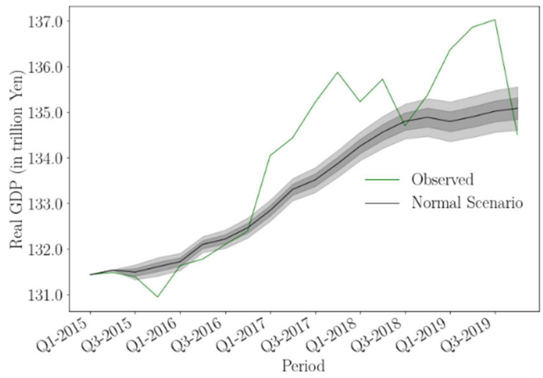
According to the Headquarters for Earthquake Research Promotion, Japan, there is a high probability of occurrence of a megathrust earthquake in the Nankai Trough region in near future. Since the Nankai earthquake will potentially impact the economically important Hanshin industrial region, it may cause severe economic losses. Therefore, we choose to study the impacts of the potential Nankai Trough earthquake. The earthquake scenario (i.e., seismic waves originated from the fault rupture) is obtained from the Cabinet Office, the Government of Japan.

In the current study, we consider the damage to the buildings only. Buildings properties of 1.8 million buildings in Osaka, Kobe, and Awaji Island (**Fig. 2**) are obtained from the GIS data of Japan. The data consists of buildings of varying number of stories and various occupancy types such as residential, commercial office, hotel, school, etc.

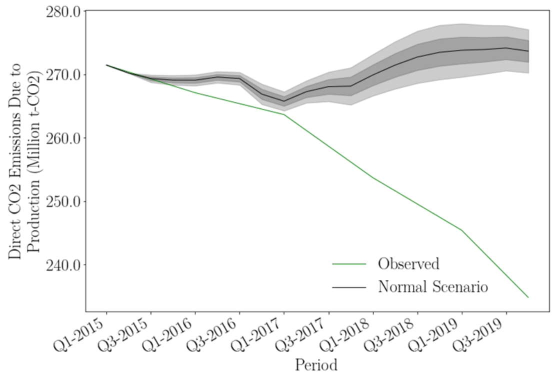
4. ESTIMATION OF CO_2-EMISSION DUE TO A POTENTIAL NANKAI TROUGH EARTHQUAKE

4.1 PROBLEM SETTINGS AND ASSUMPTIONS

(1) The first quarter of 2015 (hereinafter, Q1-2015) is the first simulation period. Monte Carlo simulation with sample size 500 is conducted for 20 quarters



(a) Real GDP



(b) CO_2-emissions

Fig. 3. Plots for validation of the methodology under normal scenario. The black line is the mean of 500 simulations, and dark and light grey regions represent 67% and 95% limits, respectively.

(from Q1-2015 to Q4-2019).

(2) CO_2-emission coefficients are calculated from the data of 2015 and assumed constant during the entire simulation.

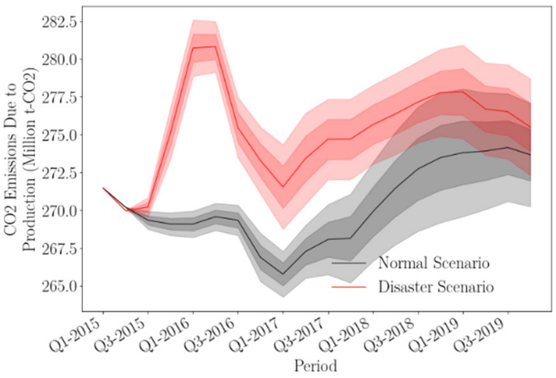
(3) The ABEM is calibrated to Q1-2015 of the Japanese economy using the macroeconomic data as explained in the previous section.

(4) The disaster is assumed to occur at the end of Q1-2015.

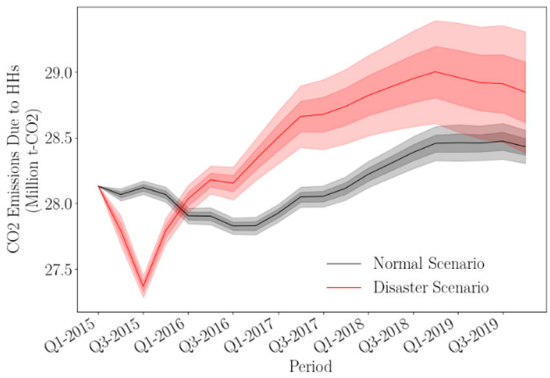
(5) Total damage to the buildings, estimated using IES and PACT (**Fig. 2**) is 15 trillion Yen out of which 6.3 trillion Yen is the loss to firms and the rest is to households. The amount of debris generated is assumed to be 25% of total damage.

(6) A worker having a damaged home is assumed to work only half-time.

(7) The impacted agents spend extra budget in the "Waste Disposal" sector to dispose of the debris and the "Building Construction" sector to repair/



(a) Total emissions due to industrial production



(b) Total emissions due to households' consumption

Fig. 4. A comparison of economy-wide CO_2-emissions due to industrial production and household consumption under normal and disaster scenario.

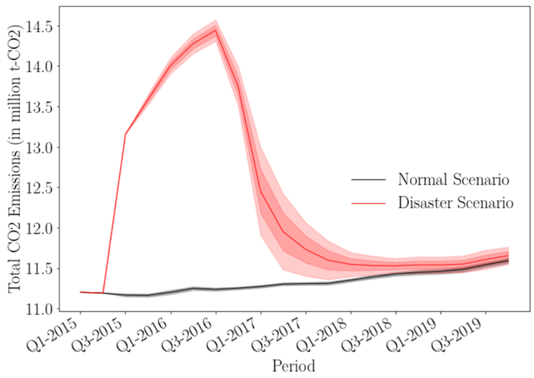
reconstruct the damaged buildings.

(8) We assume that the households receive disaster aid (equal to repair cost) from the government to repair their damaged buildings, and the firms use their own financial resources or take loans to repair the damages.

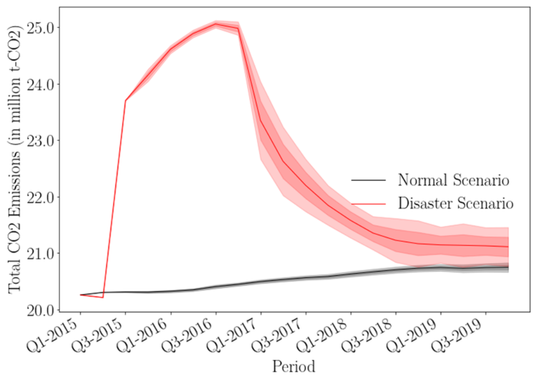
(9) The maximum consumption budget of the general government and the exporters and the quantity imported by the importers are assumed unaffected.

4.2 MODEL VALIDATION

Fig. 3 shows a comparison of model outputs with the observed values under the normal economic scenario. We can see that the real GDP simulated by the model closely follows the observed values for all simulation periods, concluding that the model can simulate the Japanese economy to a high degree of accuracy. However, quantity of CO_2-emissions is significantly different from the observations. The reason for this mismatch is that the



(a) Waste Disposal sector



(b) Building Construction sector

Fig. 5. CO_2-emissions due to Waste Disposal and Building Construction sector.

industrial CO_2-emissions coefficients are fixed to those of 2015 during the entire simulation because of the lack of updated coefficients. Technical advancements and the increasing use of renewable energy are cutting down CO_2-emissions. Therefore, we need to update the industrial CO_2-emissions coefficients as frequently as possible to accurately simulate the CO_2-emissions. In the current study, the simulations of CO_2-emissions are used for comparative analysis only.

4.3 SIMULATION OF POST-DISASTER CO_2-EMISSIONS

Quarterly estimates of CO_2-emissions due to industrial production and households' consumption are shown in **Fig. 4** under normal scenario and post-disaster scenario. In the disaster quarter, there is a decrease in production, caused by damaged capital and scarcity of labor, and consumption. Consequently, the emissions are slightly lower than the normal scenario. However, Q3-2015 onwards, the agents with damaged capital spend extra to dispose of the debris and to reconstruct/repair the damaged buildings causing a and to reconstruct/repair the damaged buildings causing a higher demand in the economy for approximately 2 years. To meet this high demand, the firms produce more, causing higher emissions. However, with the progress of recovery, the extra demand diminishes, resulting in lower production and consequently lower emissions.

Overall, the industrial production activities emit 97.7 million ton more CO_2 in 5 years in the disaster-scenario, which is approximately 9% of annual emissions in Japan. The bulk of these extra emissions is caused by the Waste Disposal and the Building Construction sector (**Fig. 5**), which contribute 19.3 million ton and 37.5 million ton, respectively.

5. CONCLUDING REMARKS

Accurate estimation of economic and environmental impacts of disasters requires large-scale fine-grained simulations of the economy and the disaster. With the help of our large-scale integrated simulator, both direct- and indirect-impacts can be estimated for the short-, medium-, and long-term. Moreover, the estimated values can be disaggregated to regions, industrial sectors, or individual economic entities. Such detailed estimation will be beneficial in forming effective disaster mitigation policies.

Although the methodology presented in this report provides a detailed estimation of the disaster-induced CO_2-emissions, its accuracy needs to be improved. Notably, we need to consider the damage to all infrastructure components; the post-disaster behavior of the agents must be improved; and updated CO2-emission coefficients must be used. Future work will focus on implementing these improvements.

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