様　式　C－１９、F－１９－１、Z－１９　（共通）

科研費
KAKENHI

科学研究費助成事業　　研究成果報告書

令和　４ 年　 ６ 月 １５ 日現在

機関番号：１２６０１
研究種目：基盤研究(B)（一般）
研究期間：2018～2021
課題番号：１８H０１６７５

研究課題名（和文）Development of an HPC enhanced system for finding fine-grained lifeline recovery plans and evaluating their long term economic performance

研究課題名（英文）Development of an HPC enhanced system for finding fine-grained lifeline recovery plans and evaluating their long term economic performance

研究代表者
Ｍａｄｄｅｇｅｄａｒ　ａ．Ｌ．（Maddegedara, Lalith）

東京大学・地震研究所・准教授

研究者番号：２０４２６２９０

交付決定額（研究期間全体）：（直接経費）　　4,200,000円

研究成果の概要（和文）：本研究では、国民経済を実大スケールでシミュレーションする高性能ソフトウェアを開発し、大規模地震災害解析手法と統合することで各種の復興計画の長期的な経済的効用を評価できるようにしました。政府機関が公開するデータを分析することで、1億2700万の主体からなる日本経済全体をシミュレーションするためのパラメータを特定しました。2015年の状態を起点に実施した2019年末までの日本経済のシミュレーション結果は観測記録と良く一致しており、開発手法が日本経済を合理的に再現できることを示しました。経済シミュレータを地震災害シミュレータと統合することで想定される復旧計画の長期的な経済性を評価可能としました。

研究成果の学術的意義や社会的意義
開発されたソフトウェアは、災害対策を立案する際、復興計画の長期的な経済パフォーマンスを総合的に評価することを可能にし、南海・東南海地震のような差し迫った大規模災害からの社会・経済復興の加速が期待できます。なお、開発したコードは、ハイパフォーマンス・コンピューティングを利用して大規模経済を1:1スケールでシミュレーションできる唯一のものです。

研究成果の概要（英文）：We developed a high performance software to simulate the national economy in 1:1-scale and integrated it with a large scale earthquake disaster simulator to comprehensively estimate the long-term economic performance of given recovery plans. Analyzing data from government sources, such as e-Stat, we identified the parameters to simulate the Japanese economy in 1:1 scale; i.e., consisting of 127 million economic entities. Starting with the conditions of 2015, we simulated the Japanese economy until the end of 2019. Good agreement of the simulation results with the observed records demonstrated that the developed model can simulate the Japanese economy to a reasonable degree. We integrated the economic simulator with an earthquake disaster simulator to seamlessly simulate an earthquake disaster in a large urban area, evaluate the degree of the damage, repair cost, recovery period, etc. of each building, and evaluate the long economic performance of potential recovery plans.

研究分野：災害科学に関する計算科学研究

キーワード：disaster recovery　economic perfoamrnce　agent-based modeling　HPC

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景

Since a mega-thrust earthquake disaster in a highly industrialized regions like in Tokai and To-nankai can significantly impact the national economy, it is vital to prepare comprehensive plans when recovering from a major disaster. Considering the business entities' heavy interdependence on each other and dependence of infrastructure, it is vital to prepare recovery plans that detail which component of lifelines and infrastructures will be recovered when. Finding such detailed recovery plans that minimize long-term economic losses is a mathematically hard problem and no solution method has been discovered yet. An attainable alternative is to solve this problem in two steps; 1) find fine-grained recovery plans (i.e., detailed plans of which component of damaged lifelines and infrastructures will be recovered when, which economic entities receive subsidizes, low-interest loans, etc.) using techniques like genetic algorithms, machine-learning, heuristic search, and 2) identify the best performing plan by comprehensively estimating their short- and long-term economic performance. Such a system will significantly contribute to the mitigation of large-scale disasters, elevating the disaster resilience of the nation.

２．研究の目的

The purpose of this research was to develop a set of high-performance software to generate potential fine-grained recovery plans, and comprehensively evaluate (i.e., checking whether each economic entity has access to lifeline networks, supply-chain networks, etc. required for contributing to the economy) the long-term economic performance of given set of recovery plans. The developed software was integrated with physics based high-resolution earthquake disaster simulator such that high resolution simulations of natural disaster, and its long-term economic impacts under a given recovery plan could be estimated comprehensively.

３．研究の方法

We used agent-based economic modeling for comprehensive evaluation economic performance, and heuristic search for generating recovery plans. High-performance computing enhanced codes were developed so that comprehensive fine-grained simulations could be performed. The developed codes were integrated with large scale physics-based disaster simulator, which was developed under K-computer project.

3.1 Agent-based economic modeling:
Economic entities' strong interdependence on each other, and their dependence of infrastructure and lifelines make *comprehensive evaluation* one of the important keyword in planning disaster recovery. To illustrate its importance, let's consider the recovery of a business firm damaged by an earthquake. Even if it manages to recover the lost capital and repair all its damaged buildings, it will not be able to start business until it can purchase necessary goods for its production from other firms, its supply networks such as gas, sewer, water are repaired, workers have recovered their damaged homes or can occupy temporary shelters, etc. Unless all such conditions are satis-fied, the firm cannot start contributing to the economy. Hence, comprehensively evaluating the progress of the economy considering the satisfaction of all such requirements of each economic

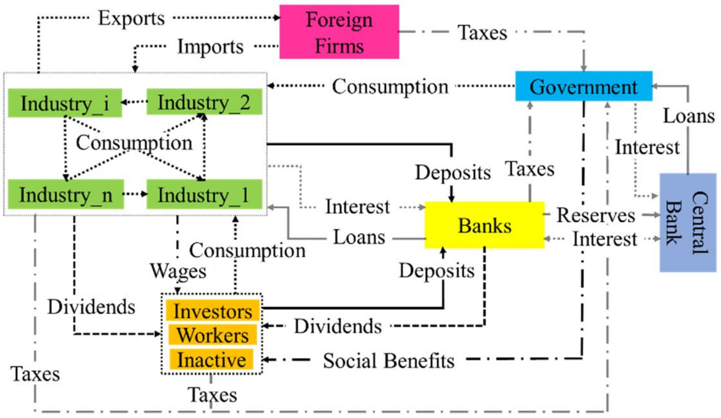


Figure 1 Schematic diagram of a typical agent-based economic model. Each industry consists of a large number of firms. The economy is connected to outside word through imports and exports.

entity is vital in evaluating the economic performance of a given recovery plan. Such comprehensive evaluations are not possible with standard economic models like DSGE, and only Agent-Based Economic Models (ABEMs) have the flexibilities required for this desired level of comprehensive evaluations. Figure 1 shows a schematic diagram of a typical ABEM. At the center, there are many industries, consisting of hundreds of thousands of firms, households of working population provide human resources to firms, government, etc. An ABEM includes all the major interactions occurring in an economy. We selected the model proposed by Sebastian et al. as the base agent-based model of this project.

3.2 HPC extension:

A major challenge in utilizing ABEM is the lack of High-Performance Computing (HPC) enhanced computer implementations capable of simulating 1:1-scale models (i.e., include each individual economic entity of a country, such as each household, each firm, etc.). Though there had been several efforts to develop HPC enhanced ABEMs, such as EURACE, software capable of simulating 1:1-scale models of large economies have not been realized to date. The main hurdle in developing such a software is the complex interactions among economic agents. We addressed the problem of generating balanced partitioning and minimizing the number of communications between ranks by partitioning the agents based on a representative employer-employee interaction graph and adopting various techniques to ensure complete availability of remaining interaction graphs at very small communication overhead. While adopted parallel computing strategies enabled us to develop a distributed parallel computing extension with reasonably high salability for small scale simulations with around 10 million agents, further improvements to the serial computing algorithms and data structures were required to attain high scalability with the target large scale simulations involving hundreds of millions of agents. Performance tests conducted using a model consisting of 330 million agents, which is equivalent to a 1:1 scale model of Euro-zone economy, produced around 80% strong scalability, which is quite high for this class of problems.

3.3 Recovery plan generation:

Allocating limited human resources (i.e., repair crews) and material to recover damaged lifeline networks and other infrastructures such that the net economic output of the nation will be maximized is a mathematically hard problem. Hence, as mentioned in the first section, our approach is to generate potential recovery plans using a method like genetic algorithm or heuristic search, using a simple objective function to maximize. We developed a greedy search algorithm guided by a simple heuristic, and a genetic algorithm. Further, we extended the greedy search algorithm to find near optimal recovery plans subjected to network constraints to find recovery plans that maximizes the output produced by the customers of lifeline networks like gas and water. In order to solve the target large scale problems, we implemented HPC enhanced codes for all the proposed recovery plan generating algorithms.

3.4 Integration with physics-based disaster simulators

In order to comprehensively evaluate a given repair plan considering the satisfaction of every need of economic entity (e.g., availability of water, sewer, power, transportation, etc. and access to market) the developed HPC enhanced economic simulator has to be integrated with other infrastructures. As the first step towards that, we integrated the developed simulator with a physics-based earthquake disaster simulator, capable of conducting large-scale earthquake

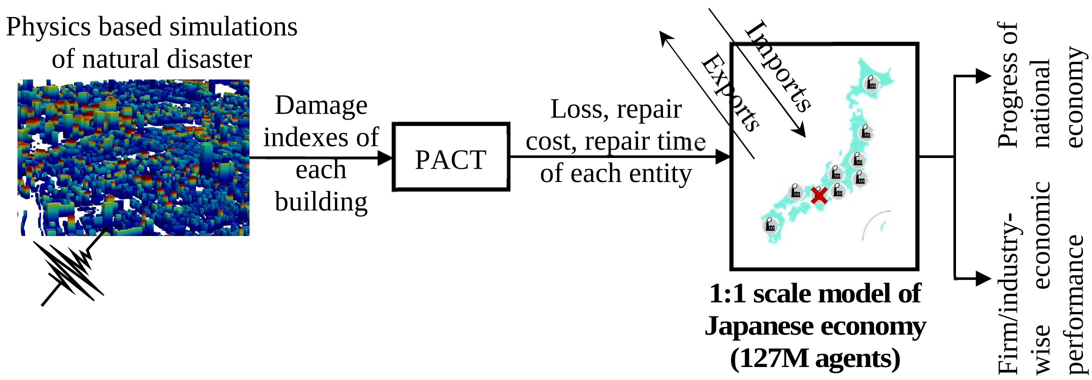


Figure 2 The HPC enhanced ABEM is integrated with physics-based earthquake disaster simulator. PACT is used to estimate the losses, repair cost, repair time, etc. based on the damage indices estimated by the disaster simulator.

disaster simulations in high spatial and temporal resolutions, as shown in Fig. 2. We used Performance Assessment Calculation Tool (PACT), developed by Federal Emergency Management Agency of the USA, for estimating the repair costs, repair time, amount of loss capital, etc. according to the damage indices from the disaster simulator.

４．研究成果

While developing a scalable HPC extension was challenging, generating input parameters, and tuning the developed ABEM to reproduce Japanese economy were equally challenging. The implemented base ABEM is a micro-founded model, which ideally requires the parameters of each agent set according to the balance sheet of its real-world counterpart. However, data at such a fine scale are too expensive to buy with the grants available for the current research. In the absence of the data of individual economic entity, we generated a consistent data set to initialize each individual agent by disaggregating the macroeconomic data published by the Cabinet Office of Japan, portal site of official statistics of Japan (e-Stat), and the Bank of Japan. The generated 1:1 scale model consisted of nearly 127 million agents.

4.1 Model validation

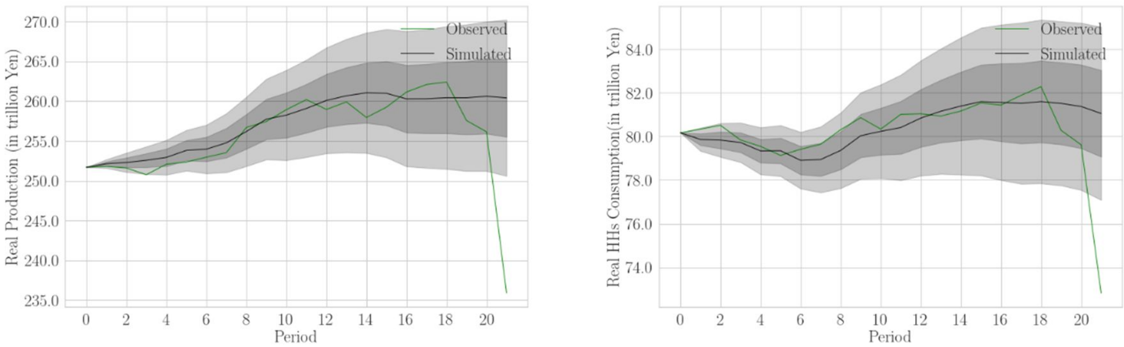
To ensure that the developed ABEM and the above generated data set can reproduce the Japanese economy to a sufficient accuracy, we conducted a validation test by comparing the model outputs with the observed economic data. In the validation test, the model is initialized according to the Japanese economy data of Q1 2015, and Monte-Carlo simulations are conducted for 22 periods starting from Q1 2015 to Q2 2020, and the results are compared with the observed data from the System of National Accounts. Figure 3 compares four macro-economic parameters. The dark and light gray regions represent ±1 and ±2 standard-deviations of uncertainty margins, respectively. As seen in Fig. 3, the simulation results are in a good agreement with the observed macro-economic data, except for the last two periods corresponding to the COVID-19 pandemic, of which the model agents are not aware. These results indicates that the developed HPC-enhanced ABEM can forecast the Japanese economy reasonably well.

4.2 Simulation of post-disaster economy

In order to demonstrate the developed integrated system, we conducted a hypothetical earthquake scenario in economically important Hanshin industrial region of western Japan. We chose the Nankai-trough earthquake scenario, as proposed by the Cabinet Office of Japan, as our hypothetical disaster scenario. In order to estimate the economic impacts, 1,786,845 buildings of Osaka city, Kobe city, Awaji island, and surrounding areas were considered in this study. Strong ground motion beneath each building, and the corresponding seismic response of each building were simulated using the physics-based earthquake disaster simulator. The calculated seismic induced maximum displacement, story drift, etc. of each floor of each building were fed into PACT to estimate the associated loss of capital, repair costs and repair time. Figure 4 shows the distribution of the repair time and repair cost of each building estimated by PACT. Finally, the repair cost estimated by PACT are assigned to the economic agents occupying the damaged buildings. Because of the lack of real data, we made several assumptions such as all the agents allocate recovery budget equal to their unrecovered capital, the households receive government aid to recover their damaged homes whereas firms use their own financing for the recovery.

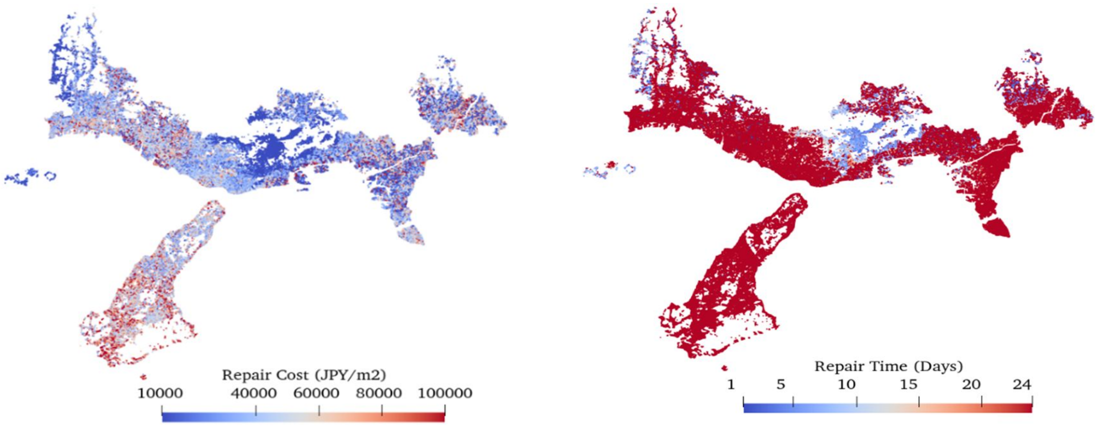
Figure 5 compares the mean values of various macro-economic indicators under disaster scenario and normal scenario. The decrease in total production is significantly small compared to total production, mainly due to the fact that the firms try to maintain their capital utilization rate at 0.85. For most of the firms, the capital loss didn’t impact their production since the loss is smaller than the extra capital stock. In case of higher capital losses, a significant decrease in production is expected and consequently, the economy will take a different recovery path. The firms keep producing at full capacity to satisfy higher demands in the economy surpassing the normal scenario production level in the second period. The figure also shows increased economic activities in the long run because of sustained higher demand and consequently higher employment in the economy.

A very simple recovery scenario, assuming that there are unlimited repair crews, no disruptions to transportation, etc., was considered in this demonstrative simulation. More complex settings, considering the behavior of economic entities during a disaster, availability of repair crews, availability of transportation networks, etc., are necessary for realistic estimations of the economic impacts and to evaluate the effectiveness of different recovery plans. We plan to continue this research to include those influential constraints to the developed integrated system, step by step.



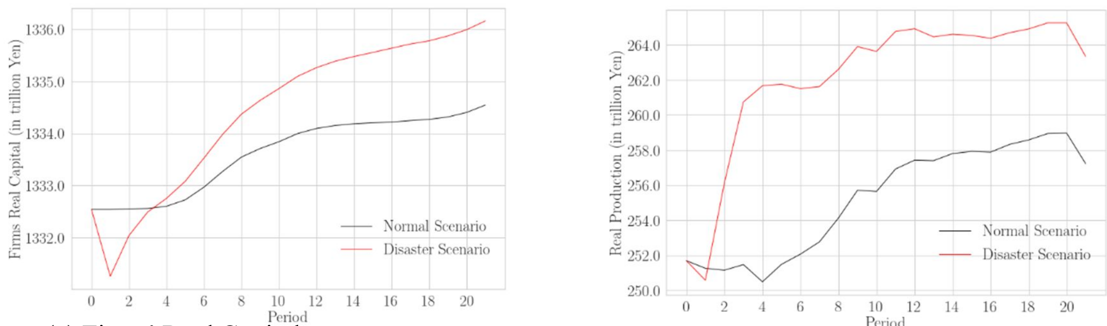
(a) Real Production (b) Real Households Consumption

Figure 3 Comparison of the results of the simulation of Japanese economy from 2015 to 2020 with the observed past records. Black line shows the mean of the simulation results while the red line shows the real-world observations. Each unit period indicates one quarter.



(a) Repair Cost (b) Repair Time (days)

Figure 4 Distribution of repair cost and repair time of each building estimated by PACT. Cost of new building is approximately 323,000 (JPY/m^2)



(a) Firms' Real Capital (b) Real Production

Figure 5 Comparison of mean values of various economic indicators under disaster scenario and normal scenario.

５．主な発表論文等

〔雑誌論文〕　計4件（うち査読付論文　3件／うち国際共著　3件／うちオープンアクセス　0件）

１．著者名 Maddegedara Lalith, Amit Gill, Sebastian Poledna, Muneo Hori, Inoue Hikaru, Noda Tomoyuki, Toda Koyo, Tsuyoshi Ichimura	４．巻 11537
２．論文標題 Distributed Memory Parallel Implementation of Agent-Based Economic Models	５．発行年 2019年
３．雑誌名 Lecture Notes in Computer Science	６．最初と最後の頁 419-433
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/978-3-030-22741-8_30	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Gill Amit、Lalith Maddegedara、Ogawa Yoshiki、O-tani Hideyuki、Ichimura Tsuyoshi、Fujita Kohei、Gatti Filippo、Hori Muneo	４．巻 -
２．論文標題 Seamless Simulations of Earthquake Disasters and Economy at 1:1 scale Utilizing Big-data	５．発行年 2021年
３．雑誌名 Procedings of the 2021 IEEE / WIC / ACM International Joint Conferences on Web Intelligence and Intelligent Agent Technology	６．最初と最後の頁 101-108
掲載論文のDOI（デジタルオブジェクト識別子） 10.1145/3498851.3498937	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Gill Amit、Lalith Madegedara、Poledna Sebastian、Hori Muneo、Fujita Kohei、Ichimura Tsuyoshi	４．巻 32
２．論文標題 High-Performance Computing Implementations of Agent-Based Economic Models for Realizing 1:1 Scale Simulations of Large Economies	５．発行年 2021年
３．雑誌名 IEEE Transactions on Parallel and Distributed Systems	６．最初と最後の頁 2101～2114
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TPDS.2021.3060462	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 4.Amit Gill, Maddegedara Lalith, Sebastian Poledna, Muneo Hori, Tsuyoshi Ichimura, Kohei Fujita	４．巻 -
２．論文標題 Development of High-performance Computing Extension for an Agent Based Economic Model for Fine-grained Post-disaster Economy Simulations	５．発行年 2021年
３．雑誌名 Proceedings of the 17th World Conference on Earthquake Engineering	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

〔学会発表〕　計9件（うち招待講演　0件／うち国際学会　9件）

１．発表者名
Maddegedara Lalith, Amit Gill, Sebastian Poledna, Muneo Hori, Inoue Hikaru, Noda Tomoyuki, Toda Koyo, Tsuyoshi Ichimura

２．発表標題
Distributed Memory Parallel Implementation of Agent-Based Economic Models

３．学会等名
International Conference on Computational Science（国際学会）

４．発表年
2019年

１．発表者名
Amit Gill, Maddegedara Lalith,Sebastian Poledna, Muneo Hori

２．発表標題
High Performance Computing Enhancement of Agent-based Economic Models

３．学会等名
Computing in Economics and Finance（国際学会）

４．発表年
2019年

１．発表者名
Lionel Quaranta, Maddegedara Lalith, Tomoo Okinaka and Muneo Hori

２．発表標題
Application of Symplectic Hamiltonian Formalism to Dynamic Crack Propagation Simulation

３．学会等名
Australian Association for Computational Mechanics（国際学会）

４．発表年
2018年

１．発表者名
Lionel Quaranta, Maddegedara Lalith, Tomoo Okinaka and Muneo Hori

２．発表標題
Development and Application of a Strain-based Formulation of PDS-FEM to the Simulation of Dynamic Crack Propagation

３．学会等名
WCCM 2018（国際学会）

４．発表年
2018年

１．発表者名 Amit Gill, Maddegedara Lalith, Hideyuki O-tani, Muneo Hori, Yoshiki Ogawa, Filippo Gatti
２．発表標題 Seamless Simulations of Earthquake Disasters and Economy at 1:1 Scale Utilizing Big-data
３．学会等名 The 2021 IEEE / WIC / ACM International Joint Conferences on Web Intelligence and Intelligent Agent Technology（国際学会）
４．発表年 2021年

１．発表者名 Amit Gill, Madeggedara Lalith, Sebastian Poledna, Muneo Hori
２．発表標題 A Scalable High-Performance Computing Implementation of Macroeconomic Agent-Based Models
３．学会等名 5th Workshop on Economics with Heterogeneous Interacting Agents（国際学会）
４．発表年 2021年

１．発表者名 Amit Gill, Maddegedara Lalith, Sebastian Poledna, Muneo Hori, Tsuyoshi Ichimura, Kohei Fujita
２．発表標題 Development of High-performance Computing Extension for an Agent Based Economic Model for Fine-grained Post-disaster Economy Simulations
３．学会等名 The 17th World Conference on Earthquake Engineering（国際学会）
４．発表年 2021年

１．発表者名 Amit Gill, Maddegedara Lalith, Sebastian Poledna, Muneo Hori, Yoshiki Ogawa, Yuki Akiyama, Yoshihide Sekimoto
２．発表標題 Unification of Integrated Earthquake Simulator and Agent Based Economic Model to Estimate Economic Impacts of an Earthquake Disaster
３．学会等名 Computational Engineering and Science for Safety and Environmental Problems（国際学会）
４．発表年 2020年

1．発表者名 Amit Gill, Maddegedara Lalith, Sebastian Poledna, and Muneo Hori
2．発表標題 An HPC Implementation of an Agent Based Economic Model
3．学会等名 Society for Social Management Systems（国際学会）
4．発表年 2019年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関