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SIMULATING THE AFTERMATH OF EARTHQUAKES ON REGIONAL ECONOMIES USING AN EXTENDED ADAPTIVE REGIONAL INPUT-OUTPUT MODEL

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Abstract: *The damage caused by earthquakes produces indirect impacts on the affected region's economic activity, including the reduction in productive capacity and economic demands from recovery activities. Compared to direct damages, these cascading impacts are difficult to quantify due to a lack of knowledge on the extent of the impacts and the laborious process for measurement. To this end, this paper summarizes our recent efforts to develop a model to simulate the regional economic recovery after the earthquake. We extend the Adaptive Regional Input-Output (ARIO) model to consider geographic heterogeneity in direct disruptions and economic structures by modelling multi-region multi-sector interactions of economic activities. Furthermore, we integrate a transportation model with an economic model to account for the interdependencies of the economic system and physical systems during the recovery. The effects of transportation disruptions on the productive capacity and supply chain are quantified and incorporated as physical constraints to post-disaster economic activities. The model outputs the estimated magnitude and duration of cascading economic impacts, using the change in value added as the performance metric. The variations of recovery and cascading impacts across different regions and sectors are examined to determine the critical areas in the system during the impact propagation and recovery stage. The described methods can be applied to both past events and hypothetical future scenarios to understand the aftermath of the earthquakes on a region's economy and identify the vulnerabilities in its existing systems.*

1 Introduction

The economic impacts of earthquakes extend beyond the direct damages. The National Research Council (1999) classifies losses into three categories: primary direct losses, secondary direct losses, and indirect losses. Primary direct losses are attributed to the immediate physical destruction resulting from the event itself. Secondary direct losses encompass additional impacts stemming from follow-on physical damage, such as fire damage from gas pipe breakage during an earthquake. Indirect losses are activity-related consequences of the physical destruction caused by the event, which can be further subdivided into short-term and long-term indirect impacts. Short-term indirect impacts encompass factors like reductions in spending, input-output losses for firms, and changes in future production, employment, and income. Long-term indirect impacts involve more enduring effects such as migration patterns, shifts in housing values, and government expenditures. Our study focuses on the economic indirect impacts after the earthquake. These indirect consequences are often more complex to quantify and comprehend than direct losses, as they involve cascading effects throughout the interconnected economic systems (National Research Council, 1999; Rose, 2004).

Adding to the complexity is the modern landscape of interdependent infrastructures and the economic interdependency between multiple regions, which challenges traditional disaster risk and resilience analysis frameworks. For instance, the 1994 Northridge earthquake caused extensive damage and interruptions to the business sites, resulting in a decline in total economic output. Among all the causes of business interruptions, the disruption to the transportation system was a main contributor. Surveys reveal that 60.4% of affected businesses faced employee inaccessibility challenges, 32.6% were unable to make shipments, and 20.1% experienced supply shortages. Consequently, the estimated losses from business interruption exceeded $6.5 billion with 27.3% resulting from transport-related interruptions (Gordon et al., 1998). Furthermore, indirect economic impacts can transcend the boundaries of immediately affected regions through supply chains, amplifying the ripple effects of disasters. For example, the 2019 Midwest floods in the United States not only disrupted the local crop production and transportation infrastructure but also caused a surge in global food prices (Food and Agriculture Organization (FAO) of the United Nations, 2019). More recently, the global response to the coronavirus 2019 (COVID-19) pandemic has underscored how lockdown policies in certain countries can have propagated impacts on the global economy (Guan et al., 2020). Similar cascading effects are anticipated in the aftermath of earthquake events.

A holistic assessment of the economic impacts of earthquakes is therefore crucial for estimating the full costs of disasters and informing decision-making for resilience investment. However, the accommodation of non-economic information, such as the interdependency between systems and spatial variability, remains a major challenge in the existing literature. In this paper, we describe our recent efforts to extend a macroeconomic model, the Adaptive Regional Input-Output (ARIO) model, to simulate the multi-regional multi-sector economic recovery process from earthquake disruptions in Section 2. We further demonstrate the model using a case study of the Tohoku earthquake in Section 3. Lastly, we describe an in-development modelling framework to consider the post-disaster economic recovery with the evolution of physical systems by integrating the macroeconomic model with transportation models in Section 4.

2 Extension of the ARIO model for multi-regional analysis

The two most common families of macroeconomic models for simulating the indirect economic impacts of an earthquake are Input-Output (I/O) models and Computable General Equilibrium (CGE) models. The I/O models primarily focus on the inter-sectoral trading relationship, while the CGE models consider the response and interactions between different economic agents to the shock. The Adaptive Regional Input-Output (ARIO) model, pioneered by Hallegatte (2008, 2014) to assess the economic aftermath of Hurricane Katrina, has seen growing application in earthquake scenarios (e.g., Wu et al. (2012); Markhvida et al. (2020)). As an extension of the I/O model, the ARIO model not only retains the strengths of explicitly reflecting economic interdependencies and capturing demand-driven changes in output but also overcomes some of the limitations of I/O models by incorporating adaptive behaviours and supply constraints (Hallegatte, 2014; Koks et al., 2016; Markhvida and Baker, 2023).

A general framework of the ARIO model is presented in Figure 1. To conduct the analysis, the model relies on essential inputs of the economic data from the region's input-output table, the observed or predicted direct loss, and the recovery curve of each sector. Additionally, the model incorporates five key economic behavioural parameters specified by the user. These parameters are crucial in assessing the adaptive capacity of each sector during the recovery phase. They include maximum overproduction capacity, time to achieve maximum overproduction, target inventory level, time of inventory restoration, and production reduction parameter (heterogeneity) that characterizes the substitution effect of the sector's output as inventories or intermediate inputs for the production of other sectors.

The ARIO model leverages input data to construct a pre-disaster economic equilibrium, applies the direct impacts to the relevant sectors, and simulates the economic system's dynamics as it reacts to shocks and regains equilibrium. The model factors in direct damage to capital stocks, resulting in a reduction of productive capital. This is also translated into reconstruction demands allocated to the construction and manufacturing sectors. Subsequently, the model simulates each sector's production, considering their respective demand, production capacity, and available inventories. This output is then distributed proportionally to other sectors or agents for their production or consumption at each time step.

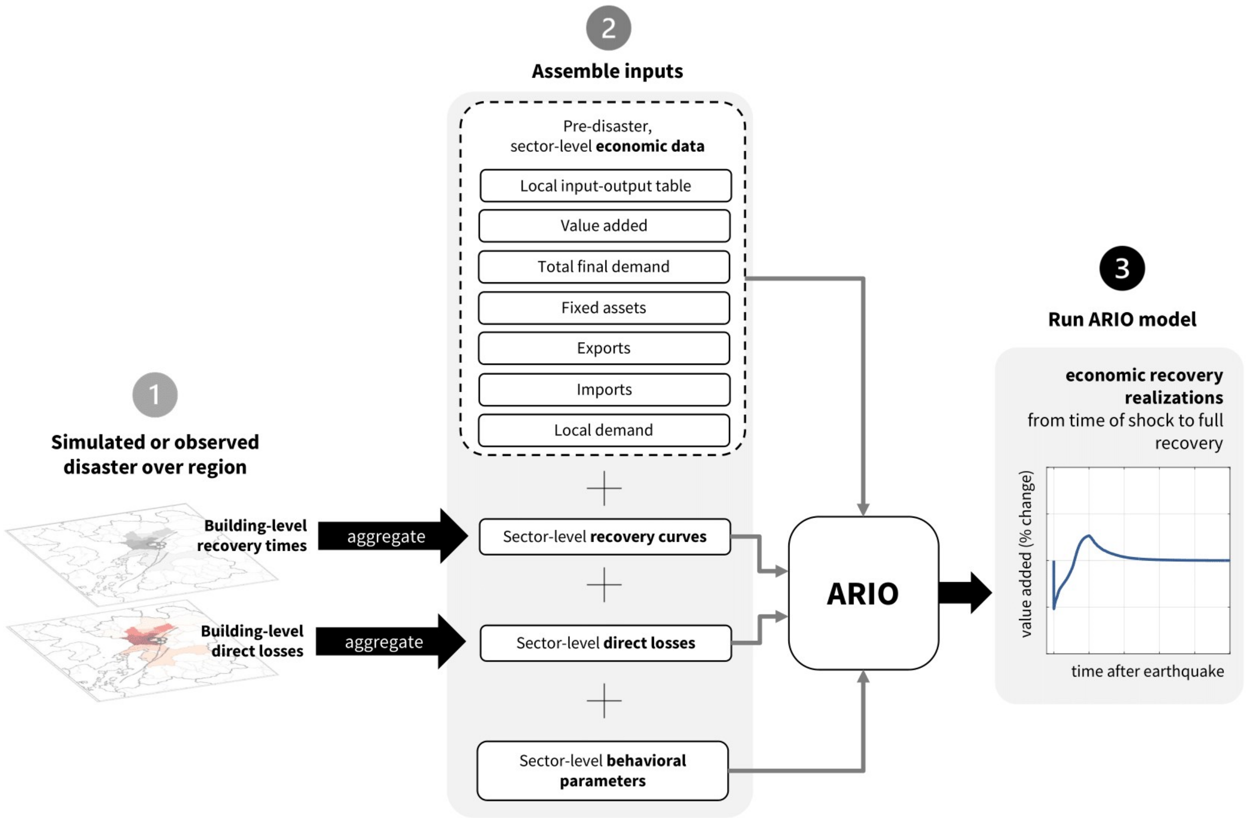
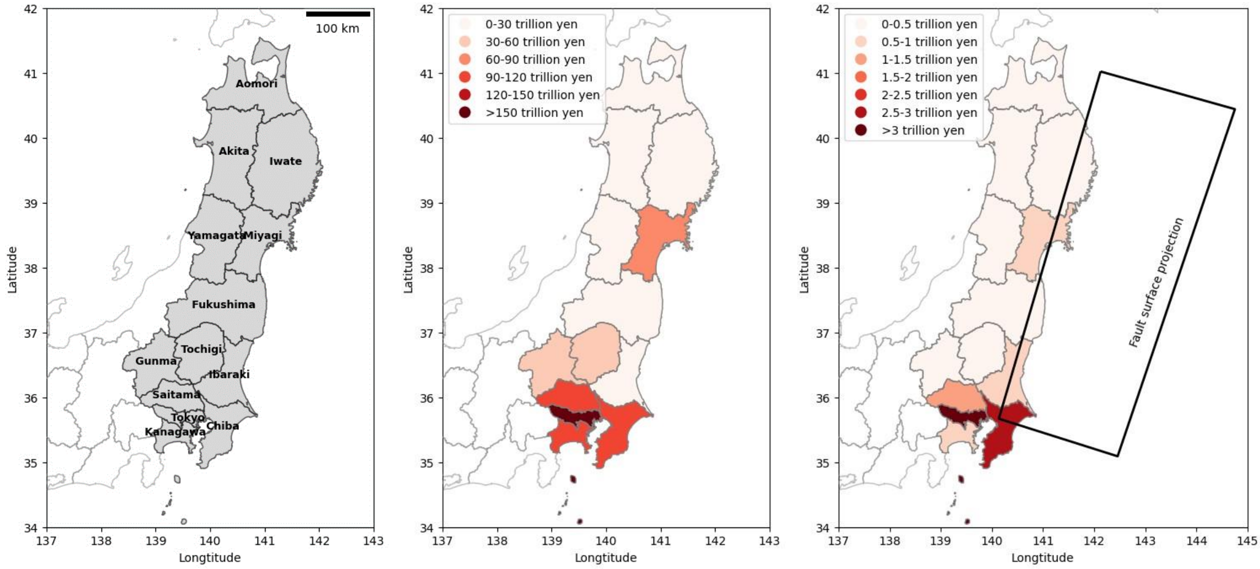


Figure 1. General overview of ARIO model. From Issa, et al. (2023).

We first describe three enhancements to the original ARIO model: (1) explicit treatment of housing damages, (2) use of empirical recovery curves to capture varying rates of reconstruction across individual sectors over time, and (3) sector-level modelling of behavioural parameters that consider sector-specific characteristics. The enhancements capture and reflect the differences in recovery resources and capacities across sectors and time, which enables a more nuanced and accurate assessment of post-disaster economic recovery dynamics. In addition, we further differentiate between local production and imports when assessing constrained production capacity resulting from losses in productive capital and supply shortages.

Building on the model improvement made through the single-regional study, we develop a methodology to evaluate the multi-regional indirect economic impacts of natural hazards at the sector level using the enhanced ARIO framework. To address the increase in computational costs with such fine-resolution analysis for multi-regions, we present a process to extract the input information for the regions of interest from an extensive dataset and discuss the trade-offs involved in selecting the study area boundary for the multi-regional analysis.

The extension to multi-regional analysis is achieved in two main stages. First, the raw data for the multi-region multi-sector economy is pre-processed to provide the necessary information about the entire economy. Second, the ARIO model is adapted to consider the pre-processed multi-regional input and geographical constraints of demand and resource distributions. We use the following steps to process the raw input-output table: (1) inspection and rebalancing the raw input-output table to achieve economic equilibrium; (2) condensing the table to an input-output table for all sectors in the study regions, based on the same data structure as the single-region input-output table; and (3) retrieving model input from the condensed input-output table. Then we adjust the model to reflect regional constraints in the economic recovery process by allocating the reconstruction demand from each sector to the construction and manufacturing sectors within the same region.



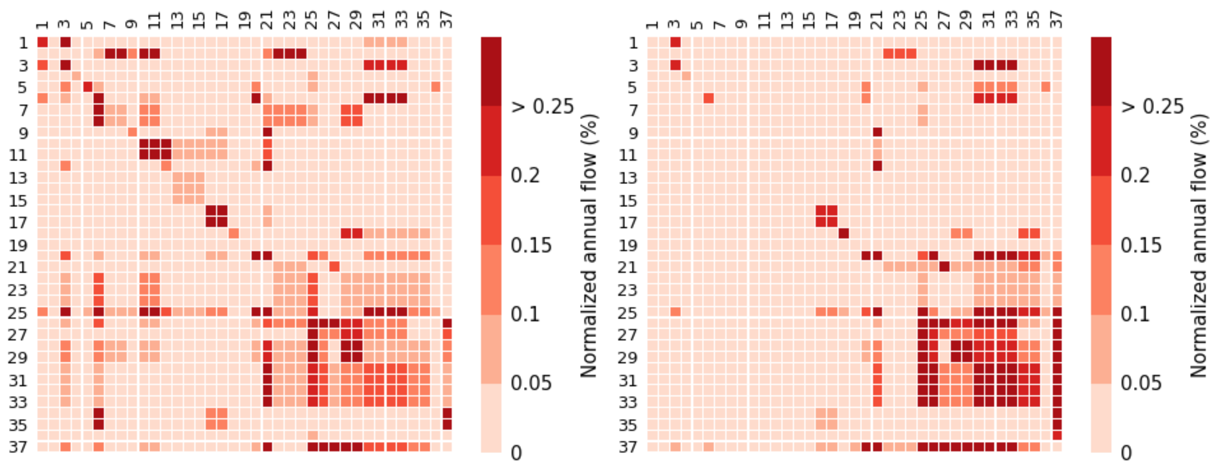
(a) (b) (c)

Figure 2. Spatial distribution of (a) prefectures, (b) fixed assets, and (c) direct damages from the Tohoku earthquake in the East-Japan region. From Zhu et al. (2023).

3 Case study of the 2011 Tohoku earthquake

The application of the model is demonstrated using a case study of the 2011 Tohoku earthquake. This devastating event struck northern Honshu, Japan, on March 11, 2011, with a magnitude of Mw 9.1. Its seismic impact was felt across most of Japan and triggered a powerful tsunami along the coastal areas. The earthquake and tsunami produced immense devastation, claiming the lives of over 15,900 individuals, leaving 3,100 missing, and causing around 6,000 injuries (Satake et al., 2014).

We consider the direct losses as the physical capital damages resulting from the earthquake ground motions. We do not account for damages resulting from secondary hazards like the tsunami or the incident at the Fukushima Dai-ichi Nuclear Power Plant, due to a lack of available data. According to insurance records, the direct losses attributed to the earthquake in the East-Japan region are estimated to be approximately 17.8 trillion yen. While these direct damages are dispersed throughout the entire East-Japan region, a significant majority of the losses are concentrated in Tokyo and Chiba in terms of monetary value (Figure 2).



(a) (b)

Figure 3. Normalized intermediate input-output relationship across all 37 sectors based on the total intermediate transactions in the region in (a) Chiba, and (b) Tokyo. The rows are selling sectors and the columns are buying sectors. From Zhu et al. (2023).

Our study focuses on the indirect economic impacts in 13 prefectures in the East-Japan region, along with regional interdependencies. The trading statistics for 37 economic sectors in each prefecture highlight the diverse economic landscape within the East-Japan region. Taking Chiba and Tokyo as examples (Figure 3), Tokyo's most robust economic connections among sectors are primarily concentrated within the service industry, while Chiba's economic linkages are more varied, spanning across different types of sectors. Moreover, distinctions exist in the trading relationship between different prefectures. Tokyo, Kanagawa, and Chiba have the most extensive trading links with other prefectures in the region, both in terms of inflows and outflows. In contrast, Akita and Yamagata have the least interaction with other prefectures. We consider both this intra-prefecture and inter-prefecture economic interdependence in the multi-regional analysis.

3.1 Indirect economic impacts for the East-Japan region

We simulate the magnitude and duration of indirect economic impacts of the earthquake at different resolutions: (1) the East-Japan region as a whole, and (2) the prefectural level. The change in value added over time is chosen as the indicator for post-disaster economic performance.

Figure 4a illustrates the overall change in value added for the East-Japan region. After the earthquake, the direct damage leads to a reduction of approximately 1.7% in the regional value added, followed by a swift recovery. Within four months, the economy's value added returns to its pre-earthquake state, followed by subsequent growth due to overproduction. In parallel, the reconstruction of the damaged capital progresses post-disaster (Figure 4b). Productive capital is restored, and the regional economy regains equilibrium roughly two years after the earthquake. The cumulative indirect loss resulting from this economic process can be calculated by measuring the area under the value added curve until the pre-earthquake level is reinstated, which represents the maximum deficit the region must absorb in the aftermath of the disaster. It is estimated to be 0.431 trillion Yen or 0.196% of the East-Japan region's pre-earthquake annual value added in the Tohoku earthquake.

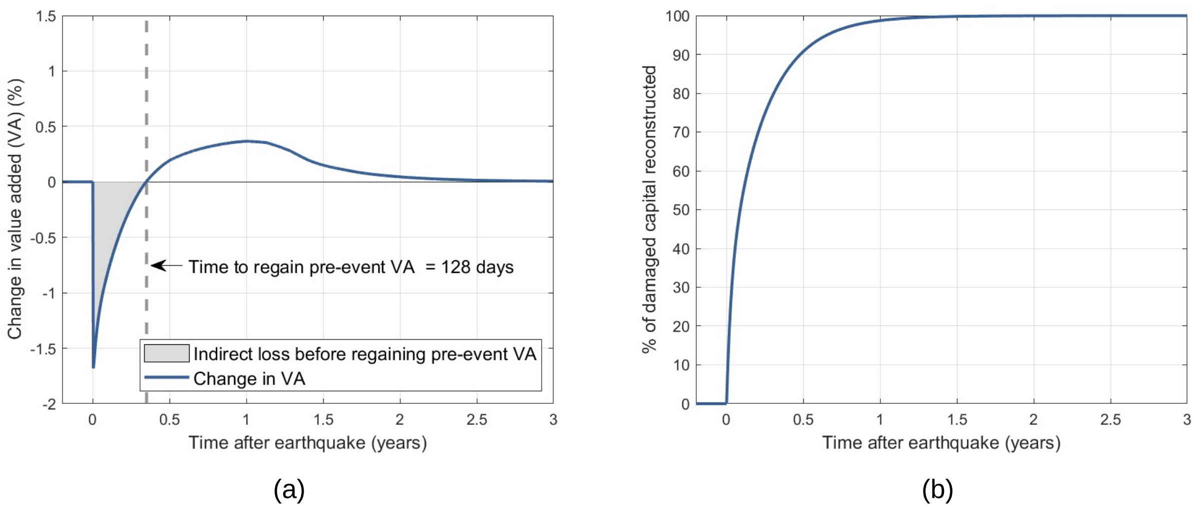


Figure 4. Post-earthquake economic performance for East-Japan region over a 3-year recovery period: (a) change in value added, and (b) reconstruction progress. From Zhu et al. (2023).

The recovery trajectory of value added for each of the 13 prefectures is presented in Figure 5, which provides a more granular depiction of impact and unveils sub-regional intricacies. Ibaraki experiences the most substantial immediate decrease in terms of change in value added after the earthquake, followed by Chiba. Generally, prefectures that undergo a more pronounced initial drop in value added are more likely to experience a significant surge in production during the recovery phase, and vice versa. In addition, prefectures that undergo less direct impacts from the earthquake, such as Aomori, Akita, Yamagata, and Gunma, demonstrate the quickest return to economic equilibrium. This highlights the varying degrees of resilience and recovery capacities across different sub-regions within the affected area.

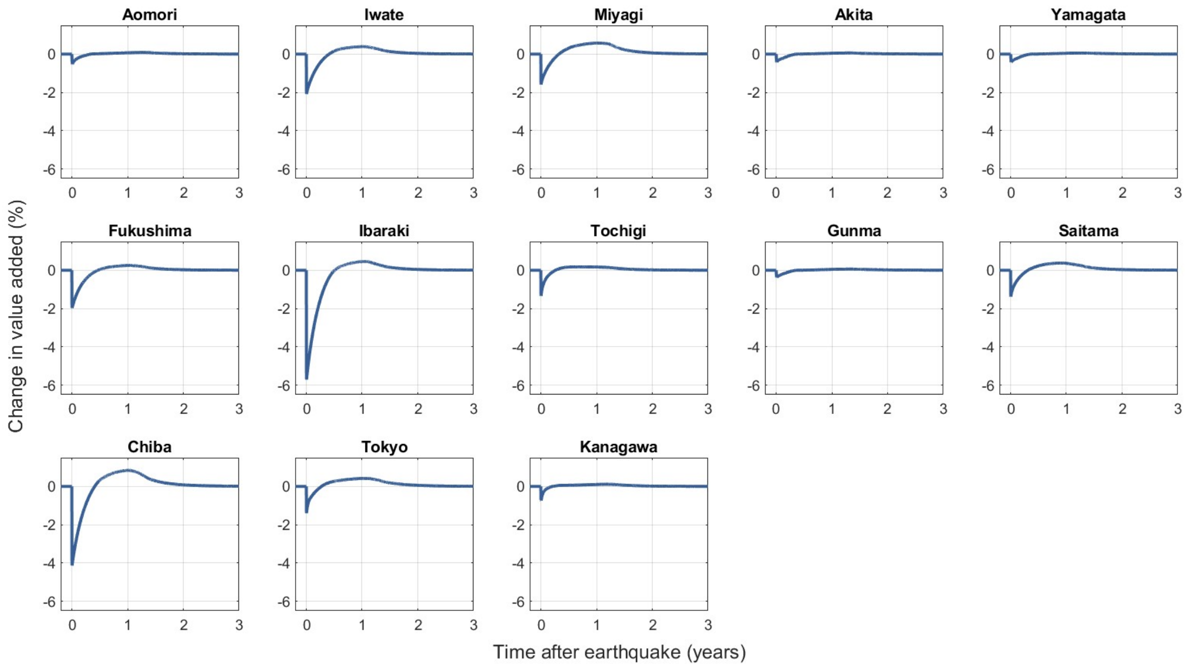


Figure 5. Post-earthquake changes in value added at prefecture level over a 3-year recovery period. From Zhu et al. (2023).

3.2 Effect of regional interdependencies

Next, we conduct a comparative analysis between single- and multi-regional approaches to evaluate the influence of inter-regional trade connections on regional economic resilience. We first run the single-regional analysis for the entire East-Japan region with the aggregated damages in each of the 37 sectors. Figure 6 compares the results with the aggregated changes in value added from the multi-regional analysis. The single-regional analysis simulates a slightly less severe decline in value added immediately after the earthquake (1.5% versus 1.7%). It also suggests a more significant overproduction during the subsequent recovery phase, leading to an underestimation of the earthquake's indirect negative economic impacts. This is attributed to its implicit assumption of an even distribution of damage and recovery across sub-regions for each sector. Conversely, the multi-regional analysis incorporates varying degrees of productive capital damage across different sub-regions, including the most severe reductions, which is likely to trigger a more substantial initial impact on the region's value added. Moreover, the multi-regional analysis is able to capture the potential bottlenecks within specific sub-regions at certain points in time, which can impede the overall recovery process.

We further conduct the single-regional analysis for each prefecture based on their individual damages and compare the results to those presented in Figure 5 for the corresponding prefecture. For prefectures with higher direct damages, the multi-regional analysis predicts smaller indirect impacts than the single-regional analysis. This is because the multi-regional approach accounts for the mitigating effects stemming from their increased trade with less affected regions. In contrast, for prefectures with minor initial damages, the indirect impacts are amplified due to their interdependence with more disrupted regions.

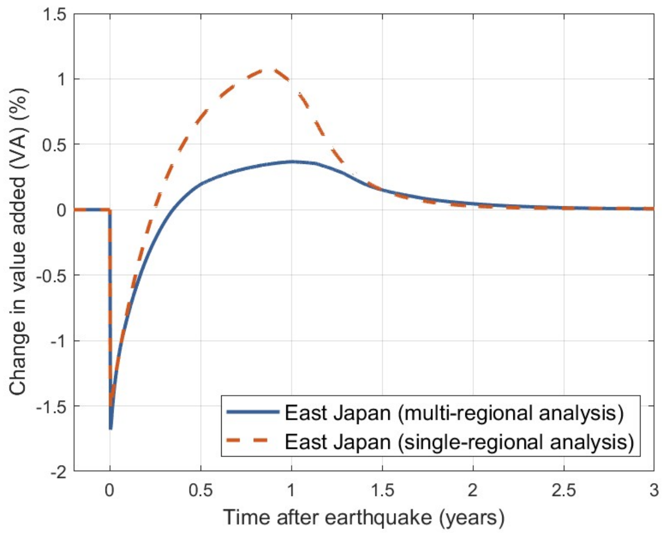


Figure 6. Post-earthquake change in value added for East-Japan region over a 3-year recovery period from multi- (blue solid line) and single-regional (red dashed line) analysis. From Zhu et al. (2023).

4 Integration of transportation and economic modelling

In future work, we plan to further integrate the disruptions from the transportation system after the earthquake in the indirect economic impact analysis. The current literature on transportation-related disruptions and their economic impacts falls short in addressing the direct physical interactions between the transportation and economic systems. Additionally, many studies do not fully grasp the dynamic interplay of these two interdependent systems during post-disaster recovery. To bridge this gap, we develop a comprehensive modeling framework that integrates transportation models with a macroeconomic model through a dynamic interface between the two systems (Figure 7).

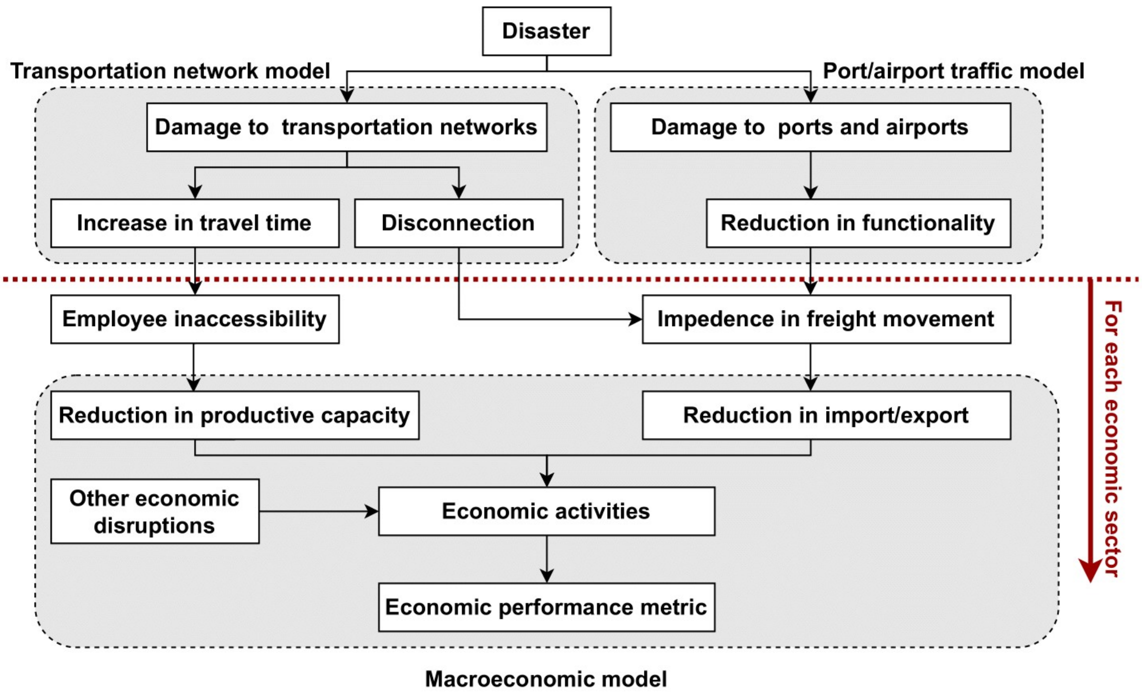


Figure 7. Framework for integrating transportation disruptions in indirect economic impact analysis.

The framework considers disruptions to both transportation networks and hubs (airports and ports) resulting from disasters and the subsequent ripple effects on the economic system. Specifically, the framework captures the impacts on both people and freight movement. When it comes to people, the disruption in transportation networks leads to increased travel times, preventing some employees from commuting to their workplaces. This, in turn, reduces available labor, thereby capping the productive capacity of affected sectors. In terms of freight-side effects, we take into account the decreased capacity of ports and airports to process the freight both into and out of the region, as well as the connectivity of these transportation hubs with the rest areas in the region. Through this approach, we estimate the quantity of imports and exports that cannot be processed for each sector and assess their consequences on both the demand and supply sides of the economic system. Note that we do not consider the impact on the movement of freight within the region, as this type of movement is more flexible in terms of scheduling compared to commuting and the impact is likely to be minimal. We further employ a dynamic modeling method, which simulates the recovery of both physical and economic systems and continuously updates the disruptive effects stemming from the physical systems to the economic system over time.

5 Conclusion

The economic interconnectedness across regions and the interdependency between the physical and economic systems can have a great influence on the post-earthquake economic landscape. Incorporating these dynamics is crucial in the analysis of indirect economic impacts of seismic events. In this study, we summarized our extensions of the enhanced Adaptive Regional Input-Output (ARIO) model to evaluate the multi-regional multi-sector indirect economic impacts of earthquakes.

Through a case study of the 2011 Tohoku earthquake, we demonstrated the capability of the multi-regional analysis in revealing sub-regional impacts and vulnerabilities. From the comparison of single- and multi-regional analysis, we evaluated the effect of geographical heterogeneity of impacts and economic ties between various sub-regions. It is found that a single-regional analysis conducted over a large study area tends to underestimate the indirect economic impacts. Moreover, the interactions between sub-regions during the post-earthquake recovery either bolster local economic resilience in the face of severe damage or heighten vulnerability in cases of minor direct losses. These findings stress the significance of considering inter-regional trade connections in assessing regional economic resilience.

Furthermore, we presented a framework to incorporate constraints to the economic recovery from transportation-related disruptions through a dynamic modelling approach. This framework addresses the interface between the transportation and economic system and that between corresponding models, considering both people and freight movements. The development and illustration of this model will be carried out as future work.

Ultimately, the tools developed in this study will empower decision-makers to enhance the estimation of the full economic cost of earthquakes and identify areas of vulnerability or criticality for system improvement. This, in turn, paves the way for the enhancement of economic resilience in the face of seismic events.

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