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Influence of Disruptive Events on Urban Carbon Neutrality Policy: A Multi-Level Comparative Study of Earthquake and Pandemic Cases

Graduate School of Media and Governance
Keio University

Hu Xujie

Abstract

Cities play a pivotal role in the global transition toward a carbon-neutral society. While numerous carbon reduction plans have been widely introduced, their implementation pathways often follow a linear trajectory, neglecting the uncertainties introduced by disruptive events. Such events can serve as inflection points for transformative change; however, their influence and the underlying mechanisms through which they affect urban carbon trajectories remain underexplored in both research and practice.

This study aims to examine how disruptive events contribute positively to urban carbon mitigation pathways and to assess the institutional potential for supporting low-carbon governance. It does so through an empirical investigation of two significant disruptive events in Tokyo: The Great East Japan Earthquake (2011) and the COVID-19 pandemic (2020). To achieve these objectives, a three-level analytical framework—Disruptive Context, Urban System, and Adaptive Practices—was developed.

Taking the Disruptive Context at macro level as background, an environmental extended input-output (EEIOA) model was constructed to trace cross-sectoral carbon flows and detect structural shifts in the urban system between 2011 and 2015. At the practices level, a life cycle assessment (LCA) approach was employed to evaluate the carbon intensity of shifts in consumer behavior during the COVID-19 pandemic, specifically in the context of online food delivery (OFD) services. By situating both cases within the same three-tiered framework, the study successfully captured the nexus effects of urban sectors under external shocks, identified systemic responses, and assessed the low-carbon potential of practices from both supply- and demand-side perspectives.

The results demonstrate that the earthquake-induced policies led to significant

reductions in CO_2 emissions: 20.84% in electricity supply, 20.54% in electricity transmission and transformation, and 8% in automobile emissions. These findings underscore the necessity of integrating responses to disruptive events into long-term decarbonization strategies, shifting from reactive recovery to proactive, emissions-conscious planning across all sectors. In contrast, the pandemic-induced behavioral changes reduced emissions in the OFD sector by at least 16%, highlighting the importance of pre-disruption education and the role of collective action by governments, industries, academia, and the public. Conceptually and methodologically, this research contributes novel insights to the field of urban climate governance.

The dissertation is structured into the following seven chapters:

- Chapter 1 introduces the research focus, emphasizing how disruptive events—typically regarded as risks—can act as catalysts for carbon mitigation. It identifies the gap between short-term reactive policies and long-term goals, setting the stage for investigating how distinct types of disruptions affect urban emissions and behavior.

- Chapter 2 provides a systematic review of disruptive events from four resilience-related perspectives: (1) mechanisms of disruption, (2) their impacts, (3) the application of the Multi-Level Perspective (MLP) framework to explain transformation opportunities, and (4) methodological approaches for quantifying carbon emissions, including EEIOA, LCA, and community-scale assessments. This chapter establishes the need for an integrated framework that links disruptions to urban carbon pathways.

- Chapter 3 introduces the three-layered framework—Disruptive Context, Urban System, and Adaptive Practices—and explains the application of EIO analysis for the earthquake case and LCA for behavioral shifts during the pandemic.

- Chapter 4 applies EEIOA to Tokyo's emissions from 2011 to 2015, revealing significant energy conversion losses and a post-earthquake shift toward coal-based power. The analysis exposes tight interlinkages among the energy, transport, and construction sectors, offering insights for post-disruption decarbonization.

- Chapter 5 evaluates CO_2 emissions from OFD during the COVID-19 pandemic, revealing that over 70% of emissions originated from food production. The findings suggest that portion control and low-emission delivery methods can significantly reduce carbon impacts.
- Chapter 6 emphasizes disruptive events as strategic entry points for climate governance. While earthquakes mainly affect upstream production sectors, pandemics influence downstream consumption patterns. The chapter advocates for the integration of disruption-informed planning into long-term strategies and promotes pre-disruption education and multi-stakeholder collaboration.
- Chapter 7 concludes by framing disruptive events as opportunities for accelerating low-carbon transitions. Despite differing emission patterns depending on event type, upstream sectors are typically more affected. Effective carbon governance, therefore, demands cross-sectoral cooperation involving governmental bodies, industries, academic institutions, and civil society. The proposed analytical framework and comparative case study approach provide practical tools for future urban carbon mitigation planning.

Overall, this study presents a novel perspective by positioning disruptive events not merely as threats but as potential catalysts for carbon reduction. Unlike previous research that focuses predominantly on planned mitigation efforts or the socio-economic consequences of disruptions, this study emphasizes how reactive disruptions can reshape urban carbon trajectories. Through the analysis of two distinct cases, it demonstrates that

different types of disruptions affect emissions through distinct mechanisms: the 3.11 earthquake triggered structural shifts in the energy sector—particularly a rise in coal use and increased construction activities—leading to heightened emissions, whereas the COVID-19 pandemic altered consumer behavior, especially in food-related consumption, with food production accounting for over 70% of emissions in OFD. These findings suggest that aligning decarbonization strategies with the structural or behavioral nature of the disruption is essential for fostering resilient and low-carbon urban systems. The conceptual framework is applicable to any types of disruptive events, such as extreme weather events, armed conflicts, or financial crises.

Despite its contributions, the study acknowledges several limitations. First, the reclassification of the input-output table—while tailored to Tokyo's context—relied on data from only two years (2011 and 2015), limiting the temporal continuity of the carbon trend analysis. Second, the OFD analysis, although methodologically rigorous, drew on outdated secondary data and did not account for common delivery items such as utensils and napkins, potentially underestimating total emissions. Future research should address these limitations by incorporating continuous and updated datasets, expanding environmental indicators, and broadening system boundaries for more comprehensive evaluations.

Keywords: Disruptive Events, Carbon Neutrality, Multi-Level Perspective, Input-Output Analysis, Life Cycle Assessment

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EEIOA – Environmentally Extended Input-Output Analysis
GIS – Geographic Information System
IOA – Input-Output Analysis
LCA – Life Cycle Assessment
MLP – Multi-Level Perspective
OFD – Online Food Delivery

1 Introduction

1.1 Research background

1.1.1 Disruptive events accelerate carbon reduction plans

The relationship between disruptive events and carbon reduction is complex and context-dependent. On the one hand, crises can function as accelerators by exposing structural weaknesses and opening up "windows of opportunity" for change. For instance, systemic shocks such as energy insecurity, supply chain failures, or extreme climate events often highlight the fragility of existing infrastructure and energy systems, prompting reconsideration of carbon-intensive pathways (Kuzemko et al., 2020). Behavioral disruptions—such as those triggered by the COVID-19 pandemic—may also lead to shifts in consumption, mobility, and lifestyle that form the basis for low-carbon practices (Le Quéré et al., 2020).

However, disruptive events can also hinder climate progress. In times of crisis, governments may prioritize short-term economic recovery or energy security over climate goals, resulting in a carbon rebound. For example, several countries restarted coal-fired power plants following energy shortages (IEA, 2022), and public investments shifted away from green sectors in favor of traditional industries (Rosenbloom & Markard, 2020). These reactions can lock systems back into high-emission trajectories.

Ultimately, disruptive events neither automatically promote nor obstruct carbon reduction plans. Their long-term effect depends on whether the new behaviors and system shifts are recognized, supported, and embedded into mainstream governance and institutional frameworks. Without policy follow-up, positive changes may remain temporary. But with proper institutionalization, disruptions may serve as entry points for long-term decarbonization.

1.1.2 Lack of an urban carbon reduction framework

Currently, mainstream climate governance frameworks—particularly at the national level—tend to emphasize the linkages between natural disasters and climate change, focusing on disaster prevention and emissions reduction policies. For example, the United States has implemented Portland's Climate Emergency Workplan, Japan issued a National Climate Emergency Declaration, Australia established the Emergency Leaders for Climate Action, and Denmark is known for Copenhagen's Climate Plan.

At the city level, however, most climate management strategies place greater emphasis on disaster resilience and infrastructure preparedness, rather than directly targeting carbon emissions. Notable examples include New York City's One NYC strategy (City of New York, 2019), Paris's Plan Climate (Mairie de Paris, 2018), and Portland's emergency climate agenda (City of Portland, 2021). While these plans demonstrate increasing attention to climate-induced risks, relatively few urban frameworks systematically integrate carbon neutrality goals into post-disaster recovery and long-term climate governance.

1.1.3 Research on disruptive events

Disruptive events are defined as sudden shocks that destabilize existing systems or institutions, creating opportunities for transformation (Geels, 2014; Smith et al., 2005). These events can vary in both nature and duration, and are commonly categorized into two types. Acute structural disruptions—such as earthquakes and tsunamis—are short-term shocks that cause immediate physical damage and systemic failures. In contrast, chronic behavioral disruptions—such as the COVID-19 pandemic—unfold over longer periods and induce sustained changes in behaviors and consumption patterns (Rosenbloom & Markard, 2020; Geels, 2020).

Existing research on disruptive events has focused on four key dimensions (Figure 1.1). First, the disruptive context examines the origin and intensity of events, such as natural disasters or pandemics, and their triggering effects on urban systems (Le Quéré et al., 2020). Second, studies on urban infrastructure explore how these events stress or transform the physical and operational foundations of cities (Heino et al., 2019). Third, behavioral change research analyzes how disruption alters consumption habits, mobility patterns, and household decision-making (Bavelet et al., 2020). Finally, governance responses investigate how institutions react to and manage disruptions, highlighting the potential for policy reform and adaptive capacity (Pelling & Manuel-Navarrete, 2011).

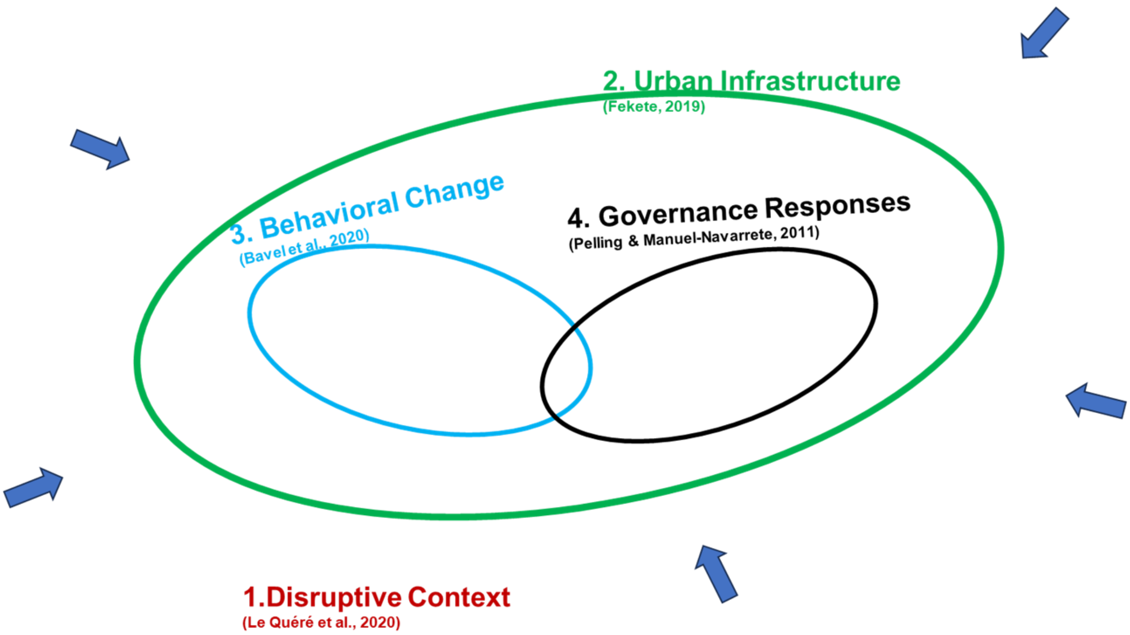

Figure 1.1 Research on disruptive events
(Figure created by the author)

These perspectives offer a multidimensional understanding of disruptive events, revealing their potential not only as threats but also as entry points for systemic low-carbon transition and urban resilience-building.

1.1.4 Rationale for case selection: the Great East Japan Earthquake and the COVID-19 epidemic

In examining the relationship between disruptive events and urban low-carbon transitions, the choice of case studies is crucial in capturing the multiple ways in which external shocks interact with urban systems and behaviors. In this study, two distinct but complementary types of disruptive events—the 2011 Great East Japan Earthquake and the 2020 COVID-19 Epidemic—are selected as empirical cases to explore how the crises affected the carbon pathways of the city. Both events affected the Tokyo Metropolitan Area, but the mechanisms of their impacts were very different, providing an ideal comparative basis for exploring the interplay between macro-level disruptive events, urban systems, and adaptive practices.

The main reason for choosing these two cases is that they represent two fundamentally different patterns of disruption:

The 2011 earthquake is a classic example of a sudden, short-term, infrastructure-orientated shock. It led to the rapid collapse of centralized energy systems, most notably the disruption of nuclear energy following the accident at the Fukushima nuclear power plant. The impacts were most visible at the level of urban systems: disrupting supply chains, destabilizing energy infrastructure and prompting large-scale shifts in energy procurement and policy.

In contrast, the New Crown epidemic represents an incremental, long-term, behaviorally oriented disruption. It has transformed urban life through restrictions on travel, telecommuting and shifts in consumption patterns. The physical infrastructure is largely intact, but social systems and daily life are subject to ongoing disruption. Of particular note, the epidemic catalyzed widespread behavioral changes in food access, travel and household energy use, making it a key case for exploring the framework's micro-level adaptive practices.

This typological contrast allows the study to examine how different types of shocks affect different entry points in the multilevel transition framework, and to assess whether and how their respective impacts lead to lasting changes in the urban carbon regime.

1.2 Research questions and hypothesis

In response to the global momentum towards carbon neutrality, cities—both major sites of carbon emissions and key areas for intervention—are increasingly adopting systematic pathways to emissions reduction. These pathways often rely on long-term planning, gradual technology adoption, and policy implementation. While these strategies have made important advances in infrastructure optimization and regulatory innovation, they largely assume a stable socio-technical environment where change proceeds in a gradual and predictable pattern. However, disruptive events such as earthquakes, epidemics, or other crises can bring sudden and often exogenous shocks to urban systems. These events may temporarily derail planned decarbonization processes or, conversely, open up new opportunities for structural adjustments. By destabilizing energy systems, governance practices, or behavioral norms, these disruptive events may trigger a range of short-term responses—some of which may have long-term effects on carbon emissions. Despite the potential importance of disruptive events, their impact on urban carbon pathways remains underexplored and undertheorized. Existing carbon neutrality research tends to view disruptions as external factors rather than potential catalysts for transformation.

Figure 1.2 illustrates that both earthquakes and COVID-19 caused significant disruptions to Tokyo's carbon emission pathways. Although a 6% reduction target was set for 2008–2012, the 2011 earthquake led to a rebound in emissions to 2007 levels, requiring four years to stabilize. Similarly, while the Zero Emissions Tokyo Strategy was introduced in 2019, emissions dropped sharply in 2020 due to the COVID-19, followed by another rebound. These cases demonstrate a common pattern in which disruptive events affect urban carbon emissions in three stages: S1 (Original stage), S2 (Disturbance stage), and S3 (Recovery stage).

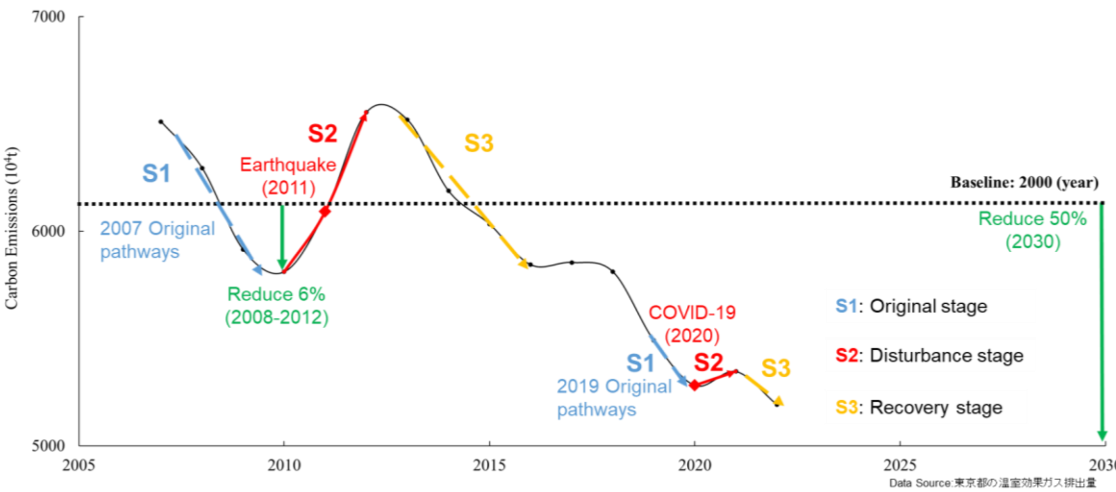

Figure 1.2 Impact of disruptive events on Tokyo's carbon emissions
(Data Source: Greenhouse gas Emissions in Tokyo. Figure created by the author.)

Against this backdrop, this study raises two interrelated research questions (Q1 and Q2) and hypothesis (H1 and H2):

Q1: The effects of both earthquakes and COVID-19 on urban carbon emissions can be divided into three stages: S1 (Original stage), S2 (Disturbance stage), and S3

(Recovery stage). Can disruptive events be used as a turning point to formulate emission reduction policies?

Q2: Despite the similarity of the changes in carbon emissions from different disruptive events, there is a significant difference in the impacts on S2 (Disturbance stage) and S3 (Recovery stage), Why?

H1: The impact of disruptive events on carbon emissions has similarities. Can disruptive events serve as a new entry point for urban climate governance frameworks?

H2: Earthquakes disrupt urban infrastructure, whereas pandemics constrain individual behavior. As a result, the magnitude and scope of carbon emission changes caused by earthquakes are significantly greater than those caused by pandemics.

1.3 Research objectives

The objectives of this research are to establish a disruptive event-driven framework for urban carbon mitigation and analyze how disruptive events change urban carbon emissions and identifies positive changes with institutional potential to support low-carbon governance. (Figure 1.3).

Specifically, this study aims to achieve the following objectives:

The first objective is to investigate the mechanisms through which disruptions drive carbon changes—whether through physical damage, behavioral shifts, or system-wide reconfigurations. These mechanisms vary by event type and affect sectors such as energy, food, transport, and construction differently.

The second objective is to clarify the reasons behind the varying magnitudes and durations of carbon emission changes. For instance, earthquakes often lead to sharp and short-term emission surges due to reconstruction demands, while pandemics trigger gradual, behavior-driven shifts that unfold over time. By comparing structural and behavioral disruptions, this study reveals how disruption type, intensity, and sectoral positioning contribute to differences in carbon impact.

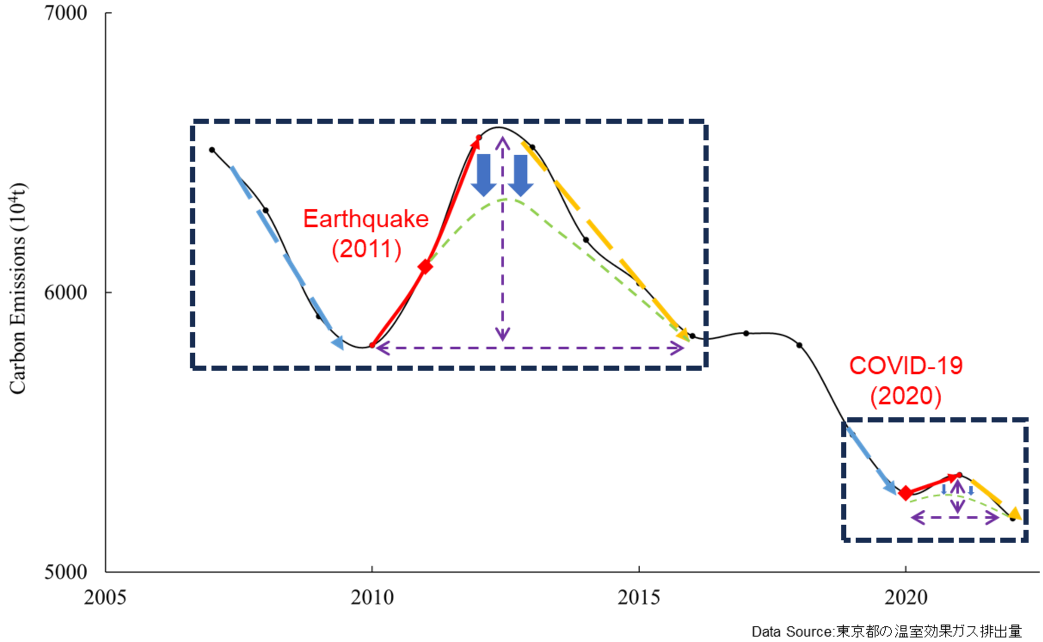

Figure 1.3 Research objectives
(Figure created by the author.)

The third objective focuses on identifying positive low-carbon changes that emerge during or after disruptions (such as reduced commuting, increased digitalization, or energy-saving practices) and exploring how these can be retained and institutionalized through policy. This involves proposing governance strategies that embed these changes into long-term urban planning and climate policies, ensuring that temporary improvements evolve into lasting, systemic transitions toward carbon neutrality.

1.4 Research significances

This study makes several important contributions to the field of urban sustainability and carbon transition research.

(a) It provides a new perspective on reducing carbon emissions through disruptive events. Previous studies have mainly focused on proactive and planned mitigation strategies, such as technological innovation and policy design, while this study proposes a complementary perspective: disruptive events, although passive and exogenous in nature, can trigger structural and behavioral changes that help reduce emissions. By considering crises as potential catalysts rather than mere threats, this study broadens the conceptual scope of carbon neutrality planning.

(b) It promotes a more systematic understanding of the impacts of disruptive events. Most existing literature on disruptive events (such as natural disasters or epidemics) focuses on their social, economic or infrastructure consequences. This study extends this discourse and shows that such events can also directly or indirectly reshape carbon emission pathways. In addition, this study challenges the idea that "change is linear or uniformly beneficial" and argues that the changes triggered by crises are multi-directional, with both risks and decarbonization opportunities.

(c) Quantify the environmental impact of disruptive events. This study seeks to quantify the environmental impacts of disruptive events by applying appropriate analytical methods tailored to the nature of each event. Disruptive events—such as earthquakes and pandemics—affect urban systems in distinct ways, requiring different methodological approaches to accurately capture their carbon implications. By matching methods to disruption type, this research provides a more precise and context-sensitive understanding of how such events reshape urban carbon flows, enabling more effective policy responses and climate governance strategies.

Altogether, these contributions enhance our understanding of how urban systems respond to disruptive events and, more importantly, how these responses can be leveraged to support lasting sustainability transformations.

1.5 Contents of thesis

This thesis explores how disruptive events affect urban carbon emissions by positioning them as entry points for understanding emission change mechanisms (Figure 1.4). The introduction highlights the uncertainties in carbon reduction policy implementation and frames the research around four dimensions: disruptive context, urban infrastructure, behavioral change, and governance responses. The literature review examines the mechanisms and impacts of disruptive events, relevant theoretical frameworks, and applicable quantitative methods. A conceptual framework is then proposed, outlining three stages of disruption: original, disturbance, and recovery. The empirical analysis focuses on two cases (earthquake and an epidemic) to assess both urban-scale and behavioral-scale impacts. Finally, the thesis offers policy recommendations for integrating disruption-responsive strategies into low-carbon urban governance.

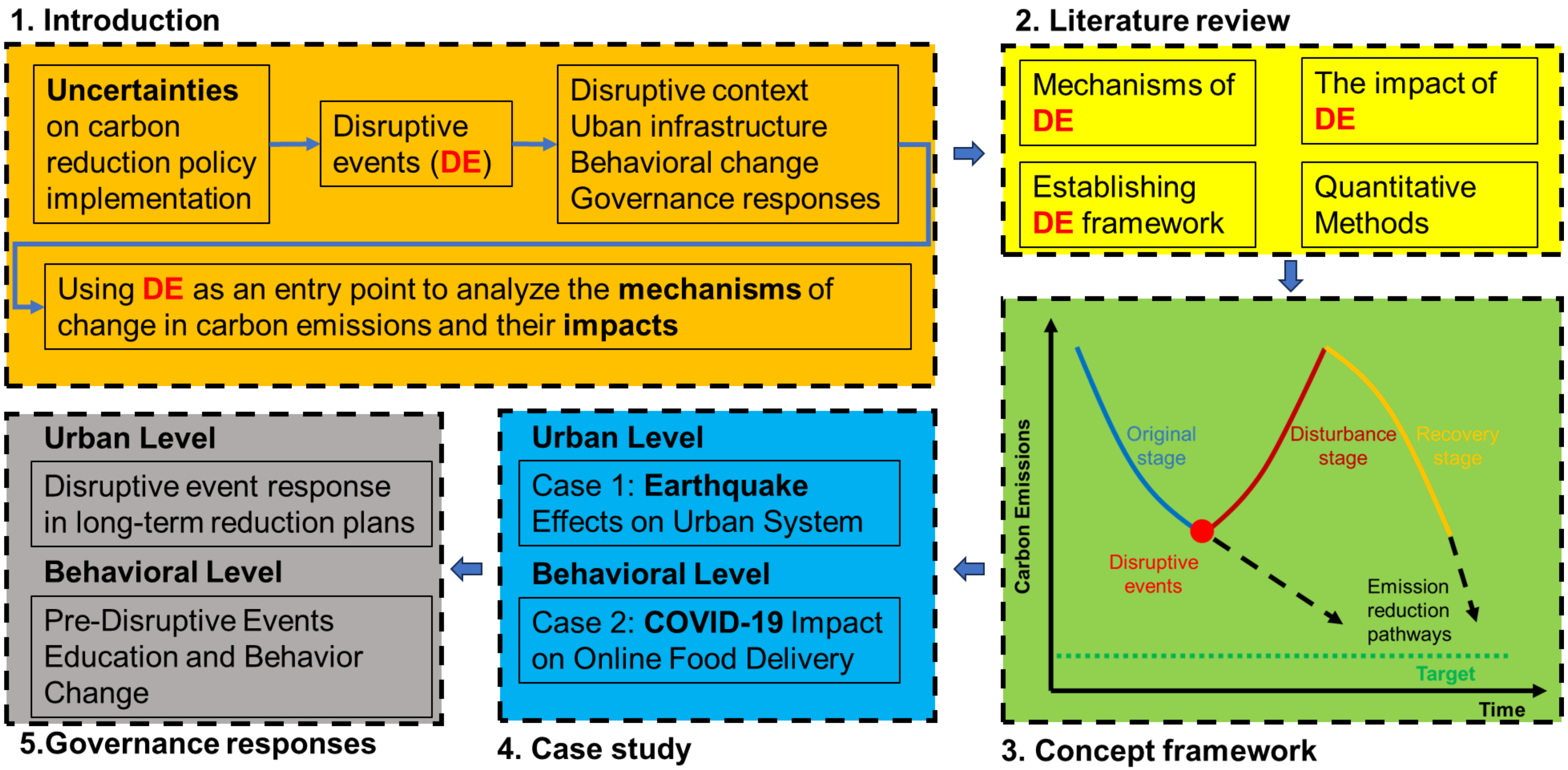

Figure 1.4 Contents of thesis
(Figure created by the author.)

2 Literature Review

2.1 Framework of literature review

Figure 2.1 shows the framework of this chapter. The literature review corresponds well to the research purpose, including mechanisms of disruption events, the impact of different disruption events, the search for a theoretical framework that meets the research purpose, and the method of quantifying carbon emissions.

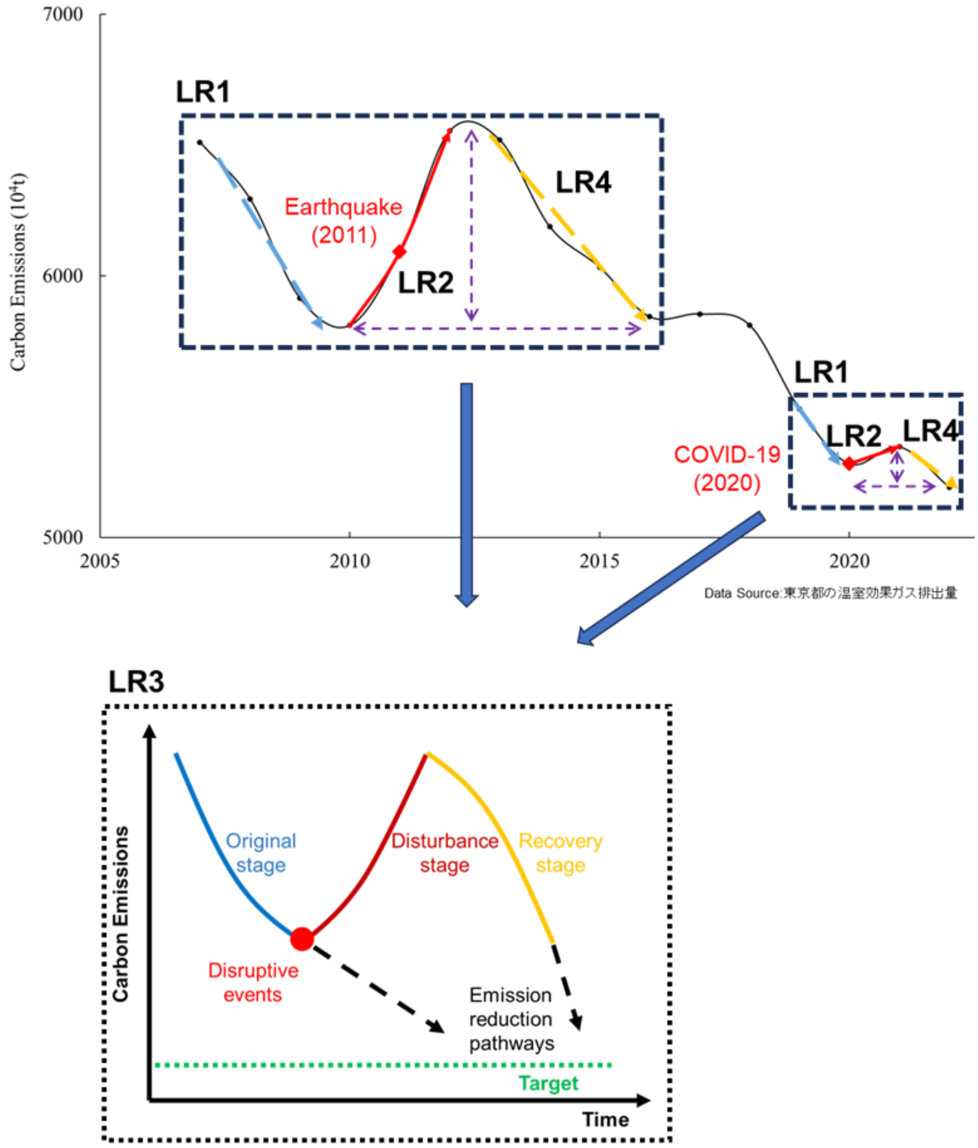

Figure 2.1 Framework of literature review
(Figure created by the author.)

2.2 Mechanisms of disruption events

Recent literature has emphasized the differing mechanisms through which various types of disruptive events affect carbon emissions. Two representative cases (earthquakes and pandemics) exemplify the contrasting rebound patterns in carbon emissions.

Earthquakes typically lead to a sharp and intensive rebound in emissions, primarily due to infrastructure damage and large-scale reconstruction. This includes significant emissions from cement, steel production, and soil carbon release (Pan et al., 2014). The immediate demand for rebuilding drives rapid spikes in CO_2, reflecting a short-term, high-intensity emission pattern.

In contrast, pandemics like COVID-19 result in a milder and more gradual rebound. During lockdown periods, emissions dropped substantially (up to 17% globally) as economic and social activities slowed (Le Quéré et al., 2020; Jackson et al., 2021). However, as restrictions eased, emissions rebounded at varying speeds depending on regional recovery patterns.

A comparative analysis reveals key differences across three dimensions:

(a) **Intensity**: Earthquakes induce abrupt, high-volume carbon increases, whereas epidemics cause slower, recovery-driven emissions.

(b) **Sustainability**: Earthquake-related emissions are immediate and short-lived, while epidemic-related rebounds unfold over longer periods, tied to behavioral and economic recovery.

(c) **Institutional Opportunities**: Epidemic rebounds can be more easily guided by green recovery policies, offering clearer windows for low-carbon interventions. In contrast, earthquake responses face more severe implementation challenges due to urgency and infrastructural complexity.

These insights highlight the importance of differentiating disruption types when designing emission mitigation strategies. Understanding these mechanisms is crucial for integrating climate resilience into both short-term responses and long-term policy frameworks.

2.3 Impact of disruptive events on urban systems

The study of how disruptive events affect urban systems has gained increasing attention across disciplines including urban planning, disaster management, behavioral science, and infrastructure resilience. These studies recognize that events such as natural disasters, pandemics, and extreme weather incidents can not only damage infrastructure but also challenge governance structures and shift behavioral norms. While important empirical insights have emerged, a key limitation remains: the lack of theoretical integration to explain how short-term disruptions translate into long-term institutional and systemic change.

This review summarizes four main thematic areas where the impacts of disruptive events on urban systems have been examined: vulnerability and resilience, governance challenges, social behavior and community response, and resilience-building efforts.

2.3.1 Urban system vulnerability and resilience

One major strand of research focuses on how disruptions expose weaknesses in existing infrastructure and service systems. Disasters act as stress tests that reveal latent vulnerabilities in energy, water, transport, and health systems (Rus et al., 2018). For example, earthquakes may highlight structural fragility, while pandemics expose limitations in decentralized resource provision.

This body of work has contributed to a growing resilience planning literature, which seeks to enhance the adaptive capacity of urban infrastructure in anticipation of future shocks. Recent studies have expanded the scope beyond physical resilience to include systemic interdependence and cascading risks (Rezvani et al., 2023). However, while vulnerability assessments are well-developed, they often stop short of exploring how identified weaknesses are addressed through long-term transformation.

2.3.2 Governance challenges and institutional response

Another important theme is how emergencies force urban governance systems to reassess resource allocation, decision-making structures, and inter-agency coordination (Kapucu, 2012). Disruptions often necessitate emergency governance measures, bypassing traditional bureaucratic pathways. This can result in temporary agility but may also reveal underlying institutional fragmentation.

Governance studies in this space have emphasized the importance of flexible, multi-scalar coordination mechanisms in crisis management. Yet, these analyses are typically bounded within the timeframe of the event, offering limited insight into how emergency governance can lead to long-term institutional innovation or policy learning.

2.3.3 Social behavior and community response

A third research area centers on behavioral adaptations at the individual and community level. Events such as COVID-19 have triggered widespread lifestyle changes, including remote work, altered mobility, and new consumption routines (Brown et al., 2015). These shifts have immediate implications for energy use, urban density, and spatial planning.

Importantly, studies have highlighted the adaptive capacity of communities in responding to crisis, from mutual aid networks to decentralized service provisioning. However, behavioral responses are often treated as temporary deviations, with less attention paid to their potential to influence long-term urban sustainability agendas, unless actively institutionalized.

2.3.4 Resilience-building and infrastructure investment

Recent work has focused on how disruptive events catalyze new investments in infrastructure and community self-organization (Kong et al., 2022). Crises often create policy windows and funding flows that accelerate projects previously stalled under normal conditions.

This "build back better" logic has been applied in post-disaster housing, energy decentralization, and digital infrastructure upgrades. Still, the literature often lacks a systematic framework to track which types of crisis-induced investments evolve into enduring systemic improvements and which are simply reactive or unsustained.

2.3.5 Synthesis and critical gap

Collectively, these four themes underscore that disruptions can serve as powerful inflection points for urban systems. They prompt technical adaptations, institutional improvisation, and social creativity. However, existing research remains fragmented across disciplinary silos, with few attempts to integrate these insights into a coherent theory of transition.

Most importantly, there is a lack of integration between empirical findings and transition theory frameworks—such as the MLP or resilience governance models—which would allow researchers to analyze how crisis-induced changes become embedded in long-term urban carbon trajectories.

2.4 Overview of multi-level perspective

The MLP has become one of the most widely adopted theoretical frameworks in sustainability transition research. Originally proposed by Geels (2002), the MLP conceptualizes socio-technical transformation as a dynamic process involving the interaction of three levels of analysis: niche innovation, socio-technical systems and the wider landscape. Over the past two decades, this framework has influenced empirical research and policy debates in areas ranging from energy transition and transport decarbonization to food systems and climate governance.

This literature review provides an overview of the conceptual foundations of the MLP, its main areas of application, ongoing debates and criticisms, as well as recent developments in the application of the framework to urban governance and crisis-driven transformation.

The MLP was developed to explain large-scale socio-technical transitions, such as the shift from horse-drawn carriages to automobiles, or from fossil energy systems to renewable energy systems. According to Geels (2002), transitions are generated through non-linear interactions between: niches (micro level): protected spaces for radical innovation and experimentation; regimes (meso level): dominant configurations of institutions, rules, technologies and infrastructures; and grids (macro level): exogenous trends and pressures, such as climate change, demographic shifts or political crises. Transformation occurs when external pressures destabilize the system, creating "windows of opportunity" for niche innovations to scale up and integrate into the mainstream (Geels & Schot, 2007). This framework emphasizes the co-evolution of technology, policy, behaviour and cultural values over time (Figure 2.2).

MLP has been used in a wide range of fields: Energy and Climate: Smith et al. (2005) and Verbong and Geels (2007) have used MLP to analyze the role of decentralization, grid reform and renewable energy in the energy transition. Mobility: MLP studies have examined the spread of electric vehicles, shared mobility, and modal shifts in transport systems (Wells & Nieuwenhuis, 2012). Agri-food systems: MLP informs research on organic food adoption, meat alternatives, and sustainable food logistics (Hinrichs, 2014; El Bilali, 2019). Urban Sustainability: The framework is increasingly applied to urban transformation, particularly when analyzing policy path dependency, multi-factor governance and low-carbon urban planning (Raven et al., 2012). The attraction of the MLP lies in its ability to bridge the gap between socio-technical complexity and longer-term policy interventions, providing a temporal and multi-factor perspective to capture systemic shifts.

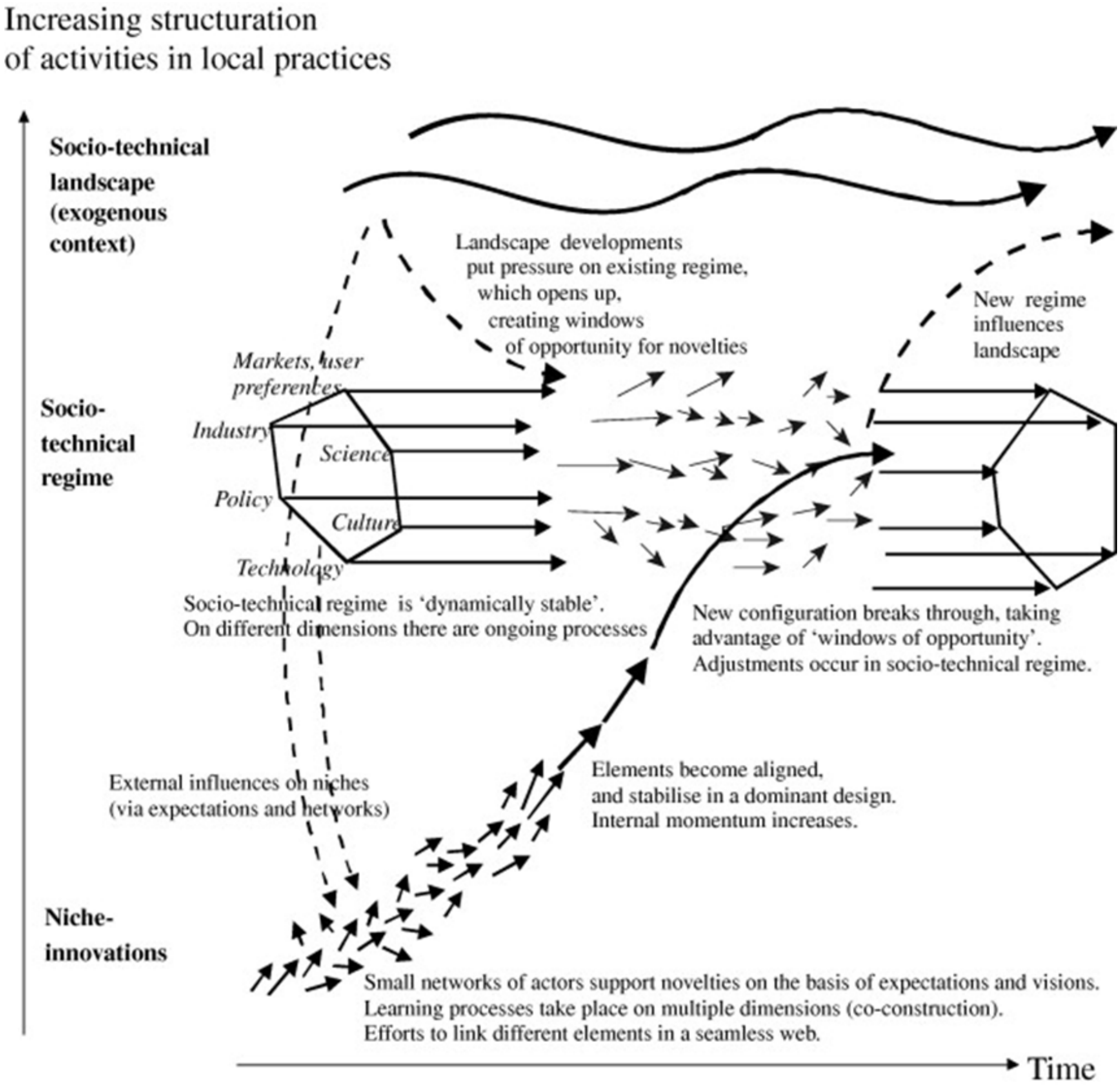

Figure 2.2 MLP framework
(Source: Geels, 2002)

Despite its popularity, the MLP has been subject to a number of criticisms: Structural determinism: Some scholars have argued that the MLP overemphasizes structural relationships at the expense of dynamism, making it difficult to incorporate the role of individual actors, power dynamics and resistance (Avelino & Rotmans, 2009; Genus & Coles, 2008). Limited urban sensitivity: Traditional MLPs are designed to analyze transitions on a national scale and often fail to adequately reflect local dynamics, spatial heterogeneity and city-specific governance processes (Coenen et al., 2012). Recent adaptations have attempted to "urbanize" the MLP to better consider place-based transition pathways. Underrepresentation of shocks and crises: the MLP initially focused on incremental transitions and is therefore less equipped to explain how sudden disruptions such as disasters or epidemics can accelerate or redirect transitions (Kanda & Kivimaa, 2020). More recent literature has begun to incorporate crisis events into MLP to remedy this shortcoming.

Several recent developments have sought to enhance the analytical capabilities of MLP: Multi-scale extension: Raven et al. (2012) advocate extending MLP to the multi-scale governance level, integrating national and local policy dynamics. Crisis-driven transitions: Studies by Pel et al. (2020) and Roberts et al. (2018) explore how environmental shocks, such as financial crises or COVID-19, can destabilize institutions and reconfigure transition trajectories. Institutional embeddedness: New research links MLPs to institutional theory, focusing on how niches gain legitimacy and become embedded in formal governance structures (Wirth et al., 2013). These extensions highlight the flexibility and capacity of MLP to integrate with other frameworks, including resilience theory, policy learning, and social innovation.

In the context of urban carbon neutrality, MLP provides a valuable framework for analyzing how experimental practices — such as energy-efficient building design, platform-based food consumption, or citizen-led mobility initiatives—can be scaled up through interactions with policy and infrastructure regimes. Furthermore, by incorporating the role of landscape-level shocks (e.g. earthquakes, pandemics), MLP can be used to examine how urban carbon pathways are not just the result of planning, but are also influenced by disruptive events that destabilize existing regimes and open new institutional windows. As shown in this thesis, mapping urban responses across the three dimensions of MLP—disruptive environments (landscapes), urban systems (regimes), and adaptive practices (niches) — provides a structured approach to tracking both immediate impacts and the potential for long-term transformation.

The multilevel perspective remains one of the most influential and adaptable frameworks for understanding sustainability transitions. Its hierarchical structure helps to clarify how innovations emerge, diffuse and become institutionalized in broader socio-technical systems. Whilst criticisms regarding agency, spatial dynamics and crisis responsiveness are valid, recent scholarship has actively addressed these gaps. Future applications of MLP, particularly in urban environments, must continue to incorporate insights from governance theory, crisis response and behavioral change. Doing so will enhance its ability to provide a practical pathway towards carbon-neutral, resilient and adaptive urban systems.

2.3 Description of the method

2.3.1 Input-output analysis

IOA is a quantitative methodology derived from economics and originally proposed by Leontief (1936) for modelling interdependencies between economic sectors. Over time, IOA has been extended and adapted as a powerful tool for environmental analysis, particularly in the areas of carbon accounting and sustainability studies. EEIOA, which incorporates physical and environmental data into economic input-output tables, has become central to understanding the structure of resource flows and emissions footprints across systems and scales.

This synthesis provides an overview of the methodological foundations of IOA, its main environmental applications (especially in terms of carbon foot printing), its strengths and limitations, and its relevance to decision-making at the city and policy levels.

The underlying principle of IOA is that economic sectors are interconnected: each sector consumes inputs from other sectors and produces outputs that are used in other sectors of the economy. Input-output tables represent this flow of goods and services. By inverting the Leontief matrix, it is possible to determine how the final demand in one sector affects the output (and environmental pressures) in all upstream sectors (Miller and Blair, 2009). Environmental Extension integrates physical flow data (e.g. energy use, emissions, water consumption) into the IO tables. This makes it possible to calculate the total environmental impacts (direct + indirect) associated with consumption, production or investment in a given sector or region (Wiedmann et al., 2007). Depending on the system boundaries, the IOA can be single-region, multi-region or global (Lenzen et al., 2013; Tukker et al., 2016).

IOA has become one of the most widely used tools for carbon footprint analysis, particularly in the following areas National carbon accounting: Countries such as the UK and China have used EEIOA to assess consumption-based carbon emissions (Wiedmann et al., 2010). Urban metabolism: IOA has been used by cities to analyze embedded emissions in infrastructure, housing, transport and food systems (Minx et al. 2013). Sectoral analysis: IOA can identify carbon-intensive industries and key intervention points throughout the value chain (Suh et al., 2006; Hertwich and Peters, 2009). Policy assessment: By quantifying indirect emissions, IOA can support life-cycle thinking in procurement, climate policy and investment prioritization (Kitzes 2013). In addition, IOA is often used to complement LCA, especially when assessing large systems or when process-level data are incomplete (Suh and Huppes, 2005).

IOA has several methodological and practical advantages: Completeness: It captures direct and indirect environmental impacts throughout the supply chain. Scalability: It can be applied at the city, national or global level. Comparability: Standardized tables allow comparisons between countries and sectors. Data Availability: IO tables are regularly published by governments and international organizations. These advantages make IOA particularly useful for identifying systemic carbon lock-in and assessing cross-sectoral policy impacts.

Despite its usefulness, IOA has some limitations: Sectoral aggregation: The use of sectoral aggregated data may mask changes at the product level or behavioral level (Wiedmann, 2009). Static structure: Traditional IOA is based on a fixed matrix of technical coefficients and assumes constant production relationships. Data Lag and Harmonization: IO tables are often outdated and may lack consistent data for environmental extensions. Lack of spatial granularity: most IOA applications are national or regional; city-level IOA requires significant downscaling and assumptions (Zheng et al., 2019). In addition, EEIOA does not directly consider consumer behavior or social factors. Therefore, it works best when used in conjunction with behavioral or system dynamics models.

Recent research has extended the applicability of IOA in a number of directions: City-level applications: Studies have applied IOA to urban carbon footprints, using MRIO models for spatial downscaling. Disturbance analysis: IOA has been used to study how shocks (e.g. disasters, COVID-19) affect carbon flows across sectors. Integration with scenario models: IOA has been combined with computable general equilibrium and input-output dynamic models to simulate long-term policy impacts (Arto et al., 2014). Hybrid approach: combining IOA with life cycle assessment, material flow analysis or GIS to bridge the gap between macro-structural and micro-behavior (Suh, 2004; Nakamura & Kondo, 2009). This development is crucial in the context of carbon neutral cities where both structural and behavioral changes must be systematically assessed.

IOA provides a robust, system-oriented framework for understanding how carbon emissions cut across the entire economic system. Its ability to reveal indirect emissions and structural interdependencies makes it indispensable in climate policy and urban carbon governance. While it has limitations, particularly in terms of behavioral granularity and data specificity, it remains a foundational methodology. Its strength lies not in micro-level precision, but in providing a structural map of carbon flows that allows policymakers to target leverage points in decarbonization pathways. Future research should continue to combine IOA with high-resolution behavioral and spatial data and explore its potential for analyzing transition disruptions and opportunities under crisis conditions.

2.3.2 Community-wide carbon analytic approach

Urban carbon accounting, which provides policymakers with a way to localize the causes of climate change, has been acknowledged as a useful approach to managing carbon emissions (Wright et al. 2011). This method is good for assessing the direct and indirect carbon emissions caused by urban and human activities (Lin et al. 2015). Currently, three main urban carbon accountings exist: a community-wide infrastructure approach, a consumption-based approach, and purely geographic accounting (Lin et al. 2015; Chavez et al. 2013; Yin et al. 2022). Purely geographic accounting only calculates direct emissions within the urban boundary and is part of the community-wide infrastructure approach. Hence, this section focuses on the community-wide infrastructure approach and a consumption-based approach.

The community-wide infrastructure approach prefers to calculate the carbon emissions of the entire supply chain from a production perspective, in-boundary and trans-boundary. Ramaswami et al. (2008) developed a community-wide infrastructure approach based on a demand-centered and hybrid LCA. They quantified building (commercial, industrial, residential, and government), transportation (cars, SUVs, trucks, and airlines), and material flow (food, cement, and fuel). Moreover, they found that Denver's carbon emissions came from energy use (52%) and transportation (30%). This approach has significant policy impacts. Lin et al. (2013) calculated carbon emissions in Xiamen City using a community-wide infrastructure approach. They found that carbon emissions from imported material flow (food, water, cement, and fuel) and cross-boundary traffic accounted for 33.84%. In addition, the per capita carbon footprint in Xiamen is lower than that in Denver, and Xiamen is a low-carbon city. Regardless of the differences in city size or boundary, the community-wide infrastructure approach seeks to encourage uniform accounting of these fundamental infrastructures across all cities to facilitate sustainable urban infrastructure planning (Chavez et al. 2013).

The consumption-based approach focuses on the cross-city flow of goods and services triggered by final consumption. Paloheimo et al. (2013) developed an approach for assessing carbon emissions from the producer and consumer perspectives. Producers include organizations related to agriculture, transport, and manufacturing, whereas consumers are generally individuals or families. This method allocates carbon emissions to consumers. Although this method is not as accurate as a consumer-oriented approach, it can show where and how emissions can be reduced. Jones et al. (2011) used consumption-based life-cycle assessment to quantify the carbon footprint of US families with multiple household sizes and different incomes in various cities. Carbon emissions come from food, energy, water, transportation, goods, and services. They found significant geographical differences in the scale of carbon emissions.

The community-wide infrastructure approach and consumption-based approach have different emphases on policy development. The former favors community-scale infrastructure planning, whereas the latter favors emission reductions through changes in consumer behavior. Many researchers recommend using both approaches to provide multidimensional information for urban carbon-reduction strategies (Baynes et al. 2011, Ramaswami et al. 2011). Moreover, assessing carbon emissions can reduce unsustainable urban resource draws, which are critical for achieving a net-zero carbon future.

Most studies calculated the carbon emissions of each element relatively independently of each other. Developing carbon-reduction policies is highly effective when analyzed from a nexus perspective.

2.3.3 Life cycle assessment

LCA has become a fundamental approach to quantifying the environmental impacts of products, services and systems throughout their life cycle. Originating in the 1960s and formalized in the ISO 14040 and 14044 standards, LCA provides a systematic framework for assessing the environmental performance of a system "from cradle to grave" (ISO, 2006a, 2006b). Over the past two decades, LCA has been widely used in climate policy, environmental product declarations, industrial ecology and urban sustainability studies. This review provides an overview of the evolution of LCA methods, their main areas of application, key methodological challenges and recent extensions to urban carbon governance.

LCA follows four steps: objective and scope definition, inventory analysis, impact assessment and interpretation. The International Organization for Standardization guidelines (ISO, 2006a, 2006b) provide a formal structure for conducting LCA, ensuring consistency and transparency. In its traditional form, LCA is process-based, using input and output data from each life cycle stage (raw material extraction, manufacture, use and disposal) to calculate cumulative environmental impacts.

A number of studies have critically examined the methodological assumptions behind life cycle assessment. For example, Finnveden et al. (2009) emphasize the importance of clearly defining system boundaries and allocation procedures, especially in comparative assessments. In addition, the distinction between attributional and outcome-based LCA (Curran, 2016) raises the important question of whether the goal of LCA is to describe the current situation or to inform future-oriented decisions.

LCA has been widely used to assess the environmental impacts of food systems, energy infrastructure, transport and buildings. In food and consumption studies, LCA has revealed the dominant role of the production phase in total emissions. For example, Notarnicola et al. (2017) reviewed more than 500 food-related LCA studies and found that primary production (agriculture, livestock) typically accounts for more than 70 per cent of emissions from processed food systems.

In the energy sector, LCA has been used to compare the carbon intensity of fossil fuels, nuclear energy, and renewable alternatives such as wind and solar energy (Pehl et al., 2017). In urban systems, researchers have used LCA to assess housing materials (Asdrubali et al., 2013), water supply and treatment systems, and transport alternatives, including electric vehicles and shared transport (Onat et al., 2015). These applications contribute to policy development in sustainable urban planning and carbon neutral pathways.

Despite its strengths, LCA faces a number of limitations. Firstly, data availability and uncertainty remain major issues. Especially in behavioral or service-oriented systems (e.g. digital platforms, food distribution), it is difficult to obtain accurate data on energy use and emissions. Secondly, system boundaries and allocation issues can seriously affect the results. For example, deciding whether to include indirect emissions (e.g., land use change, embedded energy) can change the relative ranking of alternatives (Laurent et al., 2012). Third, traditional LCA models often have limited spatial and temporal resolution. Most LCA studies assume average conditions across time and geography, which can mask site-specific changes and dynamics (Feng et al., 2020). Finally, integration with social and institutional dimensions is not well developed. While LCA is excellent at quantifying technology, it offers little insight into the socio-political conditions that enable or inhibit low-carbon transitions.

There have been recent attempts in the literature to extend the applicability of LCA to analyze emerging consumption systems and support sustainability transitions. One important direction is to use LCA to assess behavioral interventions such as low-carbon diets, product reuse or platform-based services (e.g. OFD, e-commerce). For example, Shirazi and Gholami (2021) assess the full carbon footprint of online grocery orders and highlight the importance of demand aggregation and delivery optimization.

Another promising development is the combination of LCA with decision-making frameworks such as Life Cycle Costing, Social Life Cycle Assessment or Dynamic Life Cycle Assessment. These hybrid approaches aim to consider economic, social and temporal factors to support better policy design (Zamagni et al., 2012).

In the context of urban carbon neutrality, LCA has proven valuable in identifying hotspots in urban consumption and production systems and in informing interventions beyond technological transformation. For example, combining LCA with multi-level policy frameworks such as MLPs can provide a more comprehensive understanding of how emerging practices such as sustainable food choices or mobility options can evolve from short-term experiments to institutionalized norms.

Life cycle assessment remains an indispensable tool for environmental assessment and carbon governance. Its rigorous accounting framework enables researchers and policymakers to identify carbon-intensive stages in complex systems. However, as urban sustainability challenges become more interconnected and behaviorally driven, future research must continue to expand the boundaries of LCA — methodologically, conceptually and politically. This will require not only better data and modelling, but also stronger links between technology impact assessment and social systems analysis.

3 Research Theoretical Framework Construction

3.1 Integration of theoretical framework: disruptive context, urban system, and adaptive practices

The Figure 3.1 presents a conceptual framework for analyzing how urban carbon transition pathways are influenced by disruptive events. It draws on a modified MLP and organizes the transition process into three sequential and functionally nested layers: Disruptive Context, Urban System, and Adaptive Practices. The model highlights not only the directional influence of disruption but also the recursive potential of adaptive practices to shape long-term systemic change.

At the top of the diagram, the Disruptive Context layer captures large-scale exogenous shocks that exert pressure on existing urban regimes. These disruptions may take the form of natural disasters, such as earthquakes (physical disruptions), or public health crises, such as the COVID-19 pandemic (behavioral disruptions). Unlike endogenous change or planned interventions, disruptive events are typically unanticipated, temporally condensed, and structurally destabilizing. As shown in the diagram, such shocks create "windows of opportunity" by loosening the structural coherence of the regime, thus enabling potential pathways for transformation.

In the middle layer, the Urban System represents the core socio-technical configuration that constitutes the city's carbon regime. This includes food, energy, water, transportation, building & public space, and waste. The diagram depicts the regime as being “dynamically stable” under normal conditions but vulnerable to pressure from landscape-level disruptions.

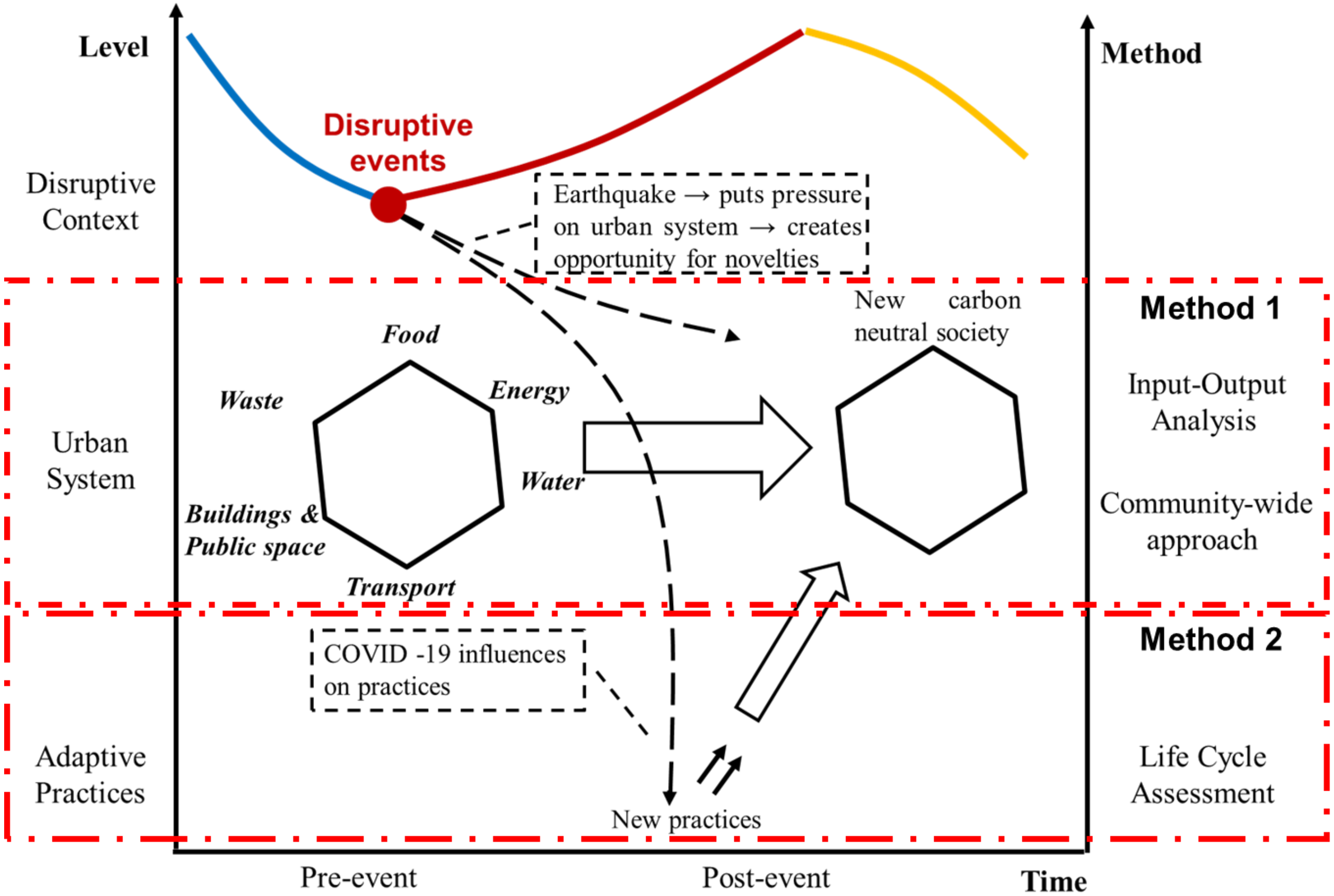

Figure 3.1 Research framework
(Figure created by the author.)

In the case of an earthquake, the system may experience immediate breakdowns in energy supply or transportation networks. In the pandemic case, behavioral regulations (e.g., lockdowns) disrupt standard service provision and demand flows. These changes trigger both reactive adaptations and structural adjustments. Notably, the figure shows the regime "opening up" through internal stress and generating new alignments of system elements—some of which may stabilize into a new dominant design.

The bottom layer captures the emergence of crisis-induced practices, situated at the niche level of the framework. These include micro-scale innovations, temporary behaviors, or improvised institutional arrangements that arise in response to system failure or disruption. For example: After an earthquake, small-scale renewable energy use or local generation may become temporarily viable; During a pandemic, the rapid adoption of food delivery services or low-contact logistics may lead to new forms of sustainable consumption.

Importantly, the framework allows for the possibility that some of these practices may scale up and feed back into regime reconfiguration, especially if reinforced by policy, societal support, and institutional embedding.

Crucially, the figure illustrates a transition arc moving from crisis-induced experimentation to regime reconfiguration. A successful pathway involves: Pressure from disruption creating destabilization; Emergence of viable practices; Alignment of system elements around these practices; Eventual absorption into a new, more resilient and low-carbon urban system. It suggests that urban carbon neutrality is not solely the outcome of planning and optimization, but also of systemic stress and innovation under pressure.

This framework reinterprets MLP through the lens of urban disruption, offering a layered understanding of how crises can serve as both threats and catalysts for sustainability transitions. By examining both top-down destabilization and bottom-up adaptive practices, the model provides a structured basis for analyzing cases like earthquakes and pandemics in the context of urban carbon transition. It shifts the research focus from linear policy planning to nonlinear pathways triggered by contingent events, enabling more realistic and adaptive transition strategies.

3.2 Implementation of the framework

3.2.1 Method 1: Quantifying the impact of earthquake on urban systems

The research framework (Figure 3.2) is based on Case Study 1. In this study, we restructured the conventional input-output table by redefining six sectors from a community-wide perspective to better capture carbon flows within urban systems. The food sector integrates agricultural production, food manufacturing, and the catering industry. The energy sector is divided into two components: energy production (including coal, gas, oil, and utilities such as electricity and heat supply) and energy consumption (covering downstream users such as manufacturing, commercial, and service industries). The building sector is constructed based on the top ten raw materials used in construction, with specific inclusion of wood, given its significant role in Japanese residential architecture. The transportation sector is limited to automobile and public transportation systems. This reclassification results in a customized six-sector IO table, which serves as the analytical basis for examining intersectoral carbon linkages and dependencies in the context of urban carbon governance.

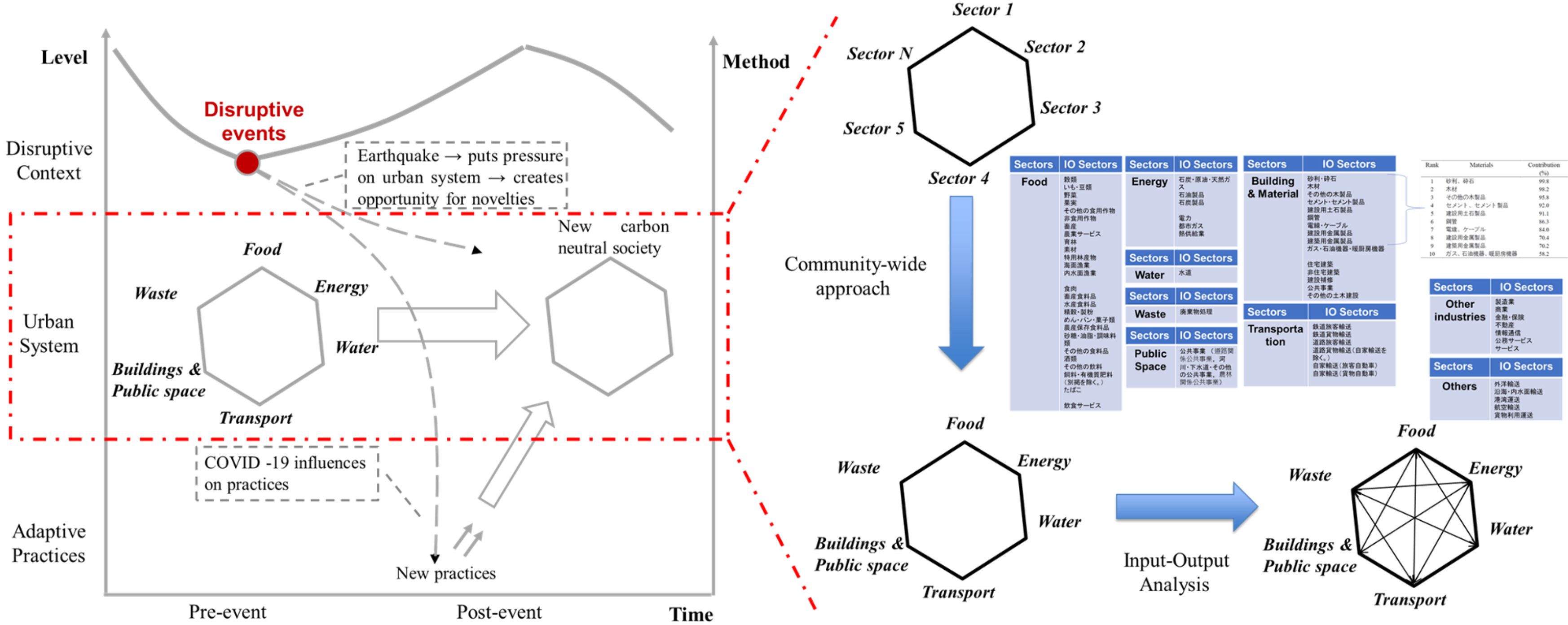

Figure 3.2 Quantifying the impact of earthquake on urban systems
(Figure created by the author.)

3.2.2 Online food delivery

By comparing energy consumption in 2019 and 2020, Living Related Services and Accommodations, Eating and Drinking Services are the top two energy consumption reducers by 19.27 % and 16.55 %, respectively (Figure 3.3). It shows that the epidemic has a huge impact on Eating Lifestyle.

OFD became very popular during the COVID-19 pandemic when restaurants were closed or limited. It connects three parts of city life—like food, transport, and waste—so it affects carbon emissions in many ways. Studying OFD helps us understand which changes in daily habits might help reduce carbon emissions in the long run.

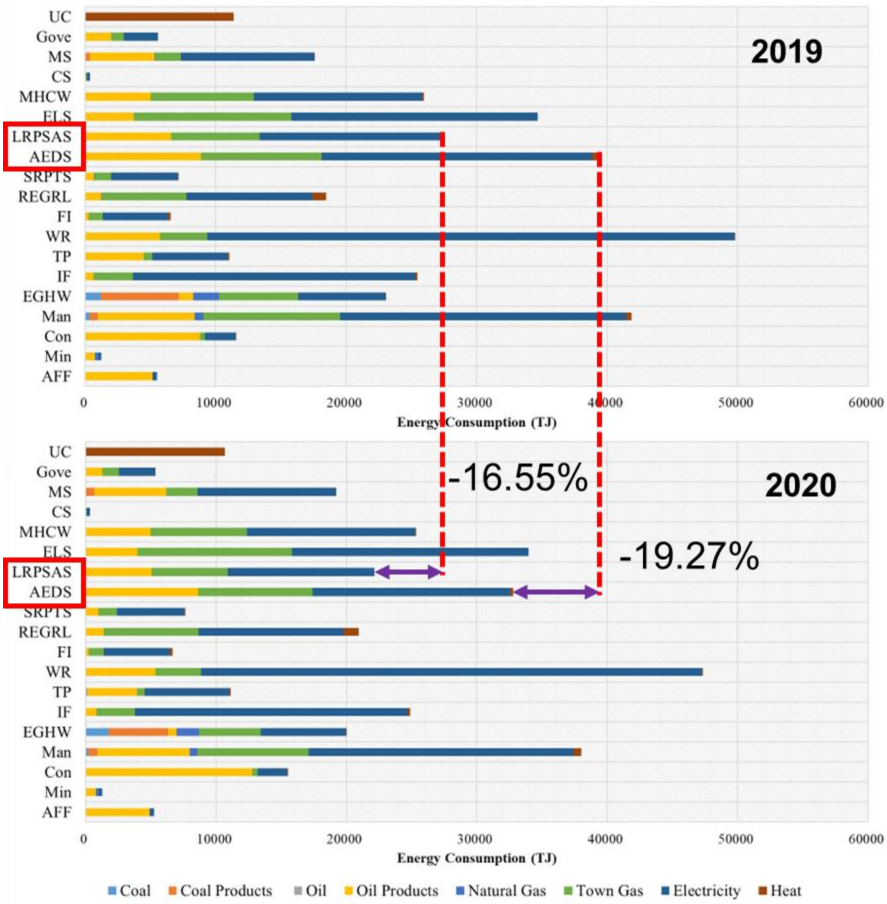

Figure 3.3 Direct energy use from 2019 to 2020
(Figure created by the author.)

3.2.3 Method 2: Quantifying the impact of COVID-19 on online food delivery

Current research on the CO_2 emissions of OFD has focused on the CO_2 emissions of OFD-related packaging from production to disposal, However, due to the limitations of the food data, most studies do not consider the contribution of food ingredients in the CO_2 emissions of OFD.

This study divides the environmental impact of OFD into four components: production, distribution, consumption and end of life/recycling. Scenario analysis in the OFD study provides a broader range of behavioral options, enabling the evaluation of which practices hold long-term carbon reduction potential. The most important point is that this study established a complete OFD database (Figure 3.4).

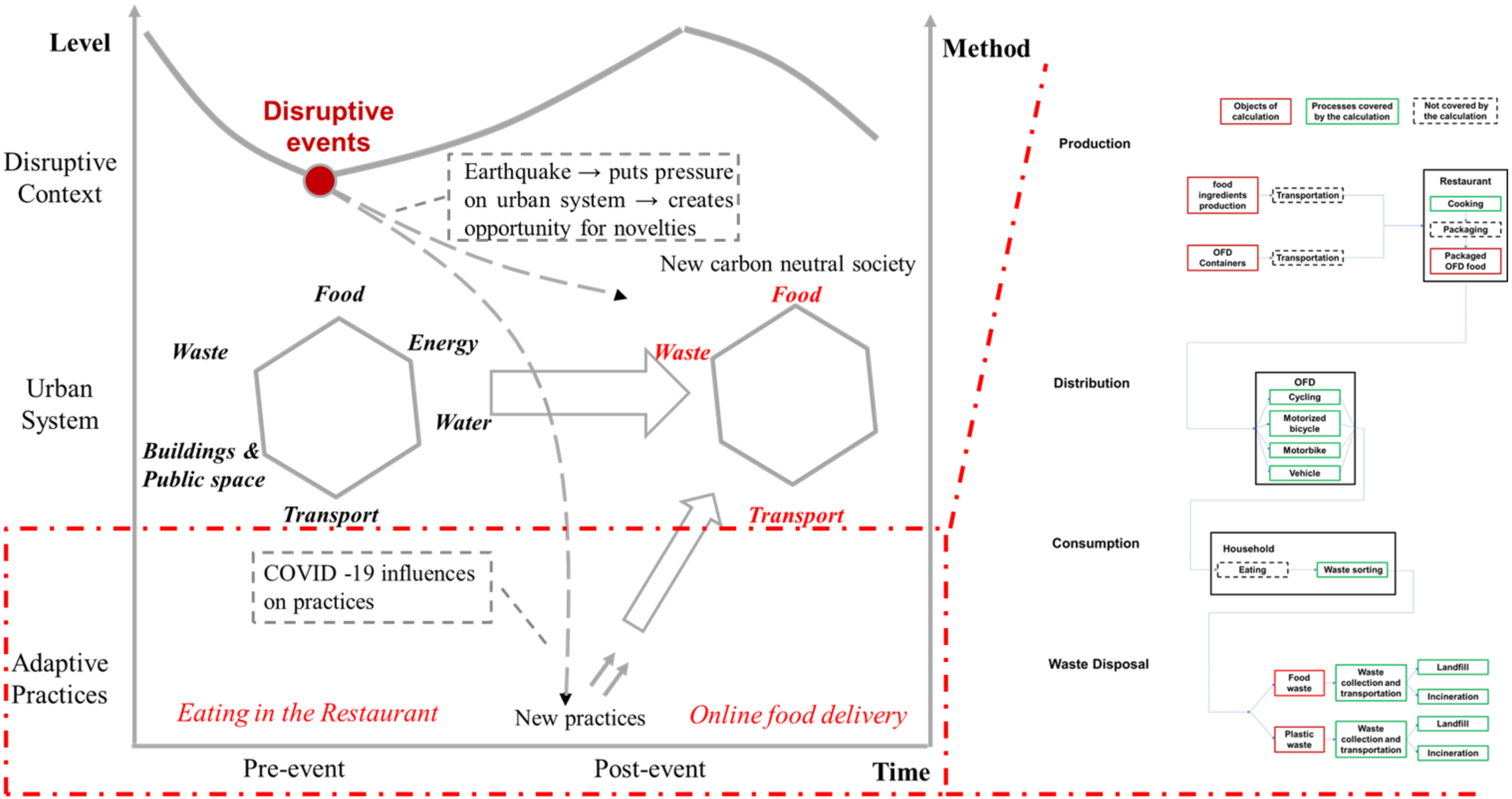

Figure 3.4 Life cycle assessment of OFD
(Figure created by the author.)

4 Case Study 1: Earthquake Impact on Urban Energy System and Carbon Emission Structure in Tokyo

4.1 Chapter introduction

Unexpected events can have profound impacts on urban resource supply and consumption. The Great East Japan Earthquake (3.11 hereafter) triggered not only the planned blackout in the Tokyo Metropolitan Region soon after the disaster but also the energy shift to fossil fuels to recover from the disfunction of Fukushima nuclear power plants. Previous research has mainly focused on the direct energy consumption and carbon emissions of different sectors while the intensity and extensity of the impact on industries and the environment have never been empirically addressed. This Chapter 4 explores energy-use efficiency and carbon emissions in Tokyo from 2011 to 2015 through a lens of nexus using EEIOA and community-wide carbon analytic approaches. Results show that the energy consumption is the largest exporter and importer of carbon emissions, whereas energy losses and carbon emissions caused by energy conversion and transmission are almost twice as much as those caused by the direct parts. Strong nexus effects among building and material, transportation, and energy consumption were observed. The 3.11 greatly impacted the energy structure and carbon emission patterns because of the increased consumption of coal for electricity. The share of energy consumption and carbon emissions by raw materials for construction also increased because of the increased demand for the reparation and reconstruction of buildings and transport systems. This structural change provided new scientific evidence for governments to implement decarbonization policies while preparing for unprecedented events.

4.2 Background

Tokyo, the world's largest metropolis with high population density and numerous industries, faces significant challenges due to escalating resource demand and various urban environmental issues such as resource depletion, pollution, waste, and ecosystem damage (Xu et al. 2021). Tokyo is also regarded as a representative of the urban energy structure in Japan, and its energy use and carbon emissions play an important role in developing urban climate change mitigation policies in Japan (Long et al. 2018). The prefectural government of Tokyo set a reduction target of 30% for energy consumption by 2030 compared with 2000 levels in 2019 and updated the target to a 50% reduction two years later (Bureau of Environment 2021). However, the carbon emissions have been reduced by 7.9% only in the last 20 years (Bureau of Environment 2015). The unprecedented earthquake may have even made the goal highly elusive. The final energy consumption dropped by approximately 12% from 2010 to 2015. However, the carbon emissions of the city returned to 2011 levels in 2015 because of the dramatic changes in the energy structure after the Great East Japan Earthquake in 2011 (Bureau of Environment 2015). This result implies that the emergency has profoundly influenced the structure for supply and demand of energy and consequently the patterns of carbon emissions of cities and even countries (Xu et al. 2021). Establishing an inventory of energy consumption and carbon emissions is important for designing sector-specific mitigation policies to achieve these reduction targets.

Cities emit more than 70% of global carbon emissions, 86% of which come from seven sectors, namely, food supply, energy supply, water supply, construction and building materials, transportation, waste and sanitation, and public/green spaces (Ramaswami et al. 2016). With massive industries and large energy consumption, cities also have an unavoidable responsibility to reduce carbon emissions. Thus, these sectors are key to energy-use efficiency and reducing carbon emissions. Understanding sectoral interdependencies, often referred to as nexus effects (Xu et al. 2021), inevitably affect the city's inputs and outputs (Wang et al. 2019). However, approaches to quantify the nexus effects remains critical. That is to assess energy consumption and carbon emissions cross sectors and to identify key sectors and productive ways to achieve energy savings and emission reductions. Currently, there are two methods to quantify the sectoral nexus effect: LCA and IOA. In general, IOA can translate economic and environmental data into physical flows using value flows (Dong et al. 2014; Tan et al. 2018) and reflect the resource consumption and emissions embodied in the trade of goods (Zheng et al. 2020). In recent years used to analyze these problems because it is useful for illustrating the supply and consumption processes of resources in various economic systems (Zhang et al. 2014; Chen et al. 2017). An increasing amount of research focuses on IOA at the national (Xu et al. 2021; Owen et al. 2018), urban agglomeration (Zhang et al. 2016; Liu et al. 2020), and city scales (Chen et al. 2016; Yang et al. 2018). Although IOA has been popularly used to explore the nexus effect of different sectors, the impacts of earthquakes on structural change of energy production and supply remains unveiled. Detailed analyses at the urban scale are needed to support the formulation and implementation of energy conservation and emission reduction policies.

Natural disasters, such as earthquakes, typhoons, and tsunamis, not only have a negative impact on human life and health but also pose serious threats to urban infrastructure, such as power plants, water conservancy facilities, and urban road networks (US Department of Homeland Security 2023). Existing research on disasters mainly focuses on post disaster reconstruction. Moreover, not many studies exist on the impact of disasters on multiple sectors, particularly the vulnerability of disasters to cross-sector interactions among food, energy, and water (Daher et al. 2021). Among them, the most direct impact comes from natural disasters that destroy energy supply systems. Natural disasters, such as earthquakes and tornadoes, can damage or even destroy urban power grid systems, cutting off the power supply to a certain area or even the entire country. This impact will also directly affect food production and water supply (US Department of Homeland Security 2023). The 2011 Great East Japan Earthquake, for instance, had a profound impact on Japan's power structure. The post-earthquake tsunami caused significant damage to the Fukushima nuclear power plant, leading to major changes in energy-related industries, particularly in the power sector (Long et al. 2021). Japan was forced to build new thermal power plants soon after the earthquake, promote renewable energy, and adjust its industrial structure (Trencher et al. 2019). This reaction can have profound impacts on energy systems and thus on greenhouse gas emissions. Therefore, Tokyo is considered a showcase to examine how energy consumption and carbon emissions can change after a dramatic change in the city's system owing to an earthquake, providing a reference for subsequent responses to similar events.

Assessing carbon emissions is vital for achieving a net-zero carbon future, with urban carbon accounting methods offering valuable insights into emission sources and pathways (Wright et al. 2011). This method is good for assessing the direct and indirect carbon emissions caused by urban and human activities (Lin et al. 2015). Currently, three main urban carbon accountings exist: a community-wide infrastructure approach, a consumption-based approach, and purely geographic accounting (Lin et al. 2015; Chavez et al. 2013; Yin et al. 2022). The community-wide infrastructure approach prefers to calculate the carbon emissions of the entire supply chain from a production perspective, in-boundary and trans-boundary (Ramaswami et al. 2008; Lin et al. 2013; Chavez et al. 2013). The consumption-based approach focuses on the cross-city flow of goods and services triggered by final demands (Paloheimo et al. 2013; Jones et al. 2011). Purely geographic accounting only calculates direct emissions within the urban boundary and is part of the community-wide infrastructure approach. The community-wide infrastructure approach and consumption-based approach have different emphases on policy development. The former favors community-scale infrastructure planning, whereas the latter favors emission reductions through changes in consumer behavior. Many researchers recommend using both approaches to provide multidimensional information for urban carbon-reduction strategies (Baynes et al. 2011; Ramaswami et al. 2011). Those studies calculate the carbon emissions of each sector independently each other while the trade-off and synergetic effects of nexus among sectors have not been explored intensively.

This study aims to quantify the nexus effects of energy-use and carbon emissions through an EEIOA based on Tokyo's input–output tables (2011 and 2015). First, we calculated energy consumption and emissions to identify the key categories for the energy conservation and emission reduction. Then, we redefined the nine categories from a community-wide perspective in the IO table, assessed Tokyo's carbon emissions change, and analyzed the interconnections between the nine categories based on embodied analysis. Finally, the impact of the earthquake on Tokyo is analyzed by comparing changes in the energy mix and carbon emissions between 2011 and 2015. Through the findings of this study, the key categories for energy conservation and emission reduction are identified, and policy recommendations are promoted to effectively achieve the goals of the Tokyo Zero Emission Strategy by 2050.

4.3 Materials and methods

4.3.1 Community-wide carbon analytic approach

The community-wide carbon analytic approach assesses carbon emissions along supply chains of seven important sectors that support urban operation (Ramaswami et al. 2021). It is reported that 86% of global carbon emissions come from food, energy, water, construction and building materials, transportation, waste, and public space (Ramaswami et al. 2016). However, most studies currently lack clear definitions for these seven categories. Therefore, this study redefines seven categories from a community-wide infrastructure approach perspective based on the IO table as summarized in Table 4.1. The food category includes agricultural products, processed food products, and the catering industry. The energy category consists of two parts: energy production and energy consumption. The energy production category includes not only the production of raw materials (coal, gas, and oil) but also the supply of electricity, gas, and heat. The energy consumption category contains many industries, such as manufacturing, commercial, and service.

Previous studies have considered cement as a building material; however, owing to the particularity of Japan, where many houses are made of wood and are delivered with all the amenities, cement and other materials, such as wood, should be considered as a building material in Tokyo. This study selects the top 10 raw materials contributing to the construction industry as construction materials according to the IO table. For the transportation, only surface transport, such as rail and road transport, is considered, whereas airline and ocean transportation are classified as other.

Table 4.1 Redefined nine categories

New categories	**Input-output sectors**	**Definition**
Food	Grains	The food category considers not only food production but also catering.
	Potatoes, beans	
	Vegetable	
	Fruits	
	Other Food Crops	
	Non-food Crops	
	Livestock	
	Agricultural Services	
	Forestry	
	Materials	
	Specialty forest products	
	Sea fisheries	
	Inland Fisheries	
	Meat	
	Livestock Products	
	Marine Products	
	Grain and flour milling	
	Noodles, bread, confectionery	
	Agricultural preserved foods	
	Sugar, oils and fats, seasonings	
	Other foodstuffs	
	Alcoholic Beverages	
	Other beverages	
	Feed and organic fertilizers	
	Tobacco	
	Food and Beverage Service	
Energy	Coal, Crude Oil & Natural Gas	The energy category includes not only the production of raw materials (coal, gas, and fuel), but also the supply of electricity, gas, etc.
	Petroleum Products	
	Coal Products	
	Electric Power	
	City gas	
	Heat supply	
Water	Water supply	

Waste	Waste disposal	
Public Space	Public works (road-related public works, river, sewerage and other public works, agriculture and forestry-related public works)	
Building & Material	Gravel and crushed stone	This study selects the top 10 raw materials contributing to the construction industry as construction materials according to input-output table.
	Lumber	
	Other Wood Products	
	Cement & Cement Products	
	Soil and stone products for construction	
	Steel Pipes	
	Electric wires and cables	
	Metal Products for Construction	
	Gas and oil appliances, heating and kitchen equipment	
	Residential Construction	
	Non-residential construction	
	Construction Repair	
	Other civil construction	
Transportation	Rail Passenger Transportation	For the transportation category, only surface transport is considered.
	Rail Freight Transportation	
	Road Passenger Transportation	
	Road Freight Transportation	
	Private Transportation (passenger Vehicles)	
	Private Transportation (freight vehicles)	
Other Industries	Manufacturing	Other industries contain the other remaining industries, which function to represent the carbon emissions of the energy consumed.
	Commerce	
	Finance and Insurance	
	Real Estate	
	Information and Communication	
	Public Service	
	Services	

Others	Oceangoing Transportation	Non-terrestrial transmissions are categorized as others.
	Coastal and Inland Water Transportation	
	Port Transportation	
	Air Transportation	
	Freight Forwarding	

4.3.2 Environmentally extended input-output analysis

Environmental extended input–output models can be used to calculate the resource consumption of different industries based on IO tables. They can be used to assess the ecological footprint (Bicknell et al. 1998; Wiedmann et al. 2006; Galli et al. 2013), water footprint (Hoekstra et al. 2007; Hoekstra et al. 2012), energy consumption, and carbon emissions (Xu et al. 2021). The calculation is shown in Eq. (1) and (2):

$$P + \varepsilon Z = \varepsilon X, \quad (1)$$

$$\varepsilon = P[X - Z]^{-1}, \quad (2)$$

where $P = [Pi]_{1\times n}$ represents a 1 × n vector that indicates the energy consumption and carbon emissions for each category; $Z = [Zij]_{n\times n}$ is the monetary input–output matrix, in units of one million yen; X is the diagonal matrix of economic output in each category. Meanwhile, $\varepsilon = [\varepsilon i]_{1\times n}$ is a $1\times n$ embodied energy intensity vector used to calculate the embodied energy flows from category i to j.

4.3.3 Direct consumption and emissions

Energy consumption can be calculated directly for each category. The types of energy in Energy Consumption Statistics by Prefecture from the Agency for Natural Resources and Energy mainly include coal, coal products, oil, oil products, natural gas, town gas, electricity, and heat. In this chapter, carbon emissions were calculated based on these eight types of energy resources (Long et al. 2018), as shown in Eqs. (3) and (4):

$$e_i = \sum E_{i,j} \times CAL_j, \quad (3)$$

$$c_i = \sum e_{i,j} \times Emissions_j, \quad (4)$$

where e_i and c_i are direct energy consumption (TJ) and carbon emissions (tC) of each category. CAL_j means the calorific value of different energy (j). $Emissions_j$ indicates the carbon intensity (tC per TJ).

4.3.4 Embodied flow analysis

In addition to the direct usage of energy and carbon emissions, production category will impact consumption and emissions categorial interlinkages called embodied consumption and emissions. The efficiencies and mechanisms of the urban system can be quantified and analyzed by measuring the embodied flows among urban categories (Zhang 2013). We can determine the vital category and pathways for energy conservation and emission reduction by analyzing embodied flows of energy and carbon in the urban system (Li et al. 2017; Cai et al. 2019). Therefore, sectoral embodied flows of consumption and emissions must be considered. The embodied flows reflect the energy consumption and carbon emissions embodied in the trade of goods. Embodied flows can be quantified based on environmental IOA (Xu et al. 2021), as shown in Eq. (5):

$$F_{ij}^{fewc} = \left[f_{ij}^{fewc}\right] = \varepsilon^{fewc} Z, \quad (5)$$

where F_{ij}^{fewc} is the embodied flow from category i to j, $Z = [Zij]_{n \times n}$ is the monetary input–output matrix, and ε^{fewc} is the diagonal matrix of the embodied intensity.

4.3.5 Energy conversion loss

According to the definition of the Agency for Natural Resources and Energy, energy conversion loss means that when different industries purchase energy (electricity and heat) from the outside, the energy used to generate and transform energy and lost in transmission should be allocated to these industries. This portion of energy consumption is referred to as indirect consumption (Agency for Natural Resources and Energy. 2018a).

The average energy loss per unit of electricity and heat consumed is determined by multiplying the energy conversion losses associated with the supply of electricity and heat by the amount of electricity and heat imported and consumed by each category (Agency for Natural Resources and Energy. 2018a) as follows:

$$X_{ij} = (F_i \div U_i - E_i) \times U_{ij}, \tag{6}$$

where X_{ij} is the energy loss of energy type i in category j. F_i is the number of inputs for the production of energy type i (unit: MJ), for example, thermal power generation through coal inputs. U_i is the number of outputs for producing energy type i (electricity unit: kWh, heat unit: kg). E_i is the energy consumption per unit of energy type i (electricity is 3.60 MJ/kWh, heat is 2.57 MJ/kg). U_{ij} is the amount of energy type i consumption in category j.

In the final electricity and heat consumption, according to the statistical data provided by the Agency for Natural Resources and Energy, the direct electricity and heat consumption of each industry and the energy lost in energy generation by external energy generation companies can be obtained. Direct consumption and external losses are combined to obtain the final energy consumption of different industries (Agency for Natural Resources and Energy. 2018b).

Carbon emissions related to electricity and heat are not emitted during the usage phase but during the generation phase. Therefore, carbon emissions from the direct use of electricity and heat by different industries are zero. When external power companies generate electricity and heat to meet the energy needs of different industries, the carbon emissions associated with fuel combustion should be considered (Agency for Natural Resources and Energy. 2018b). These data were obtained from the Agency for Natural Resources and Energy statistics.

4.3.6 Research framework

Figure 4.1 illustrates the framework for evaluating the earthquake's impact on energy use and carbon emissions from a nexus perspective. Initially, direct energy consumption and carbon emissions are quantified using IO tables, categorized into 11 categories. Subsequently, indirect energy consumption and carbon emissions are computed across different categories, factoring in energy conversion losses. The IO tables are then reorganized from a community-scale viewpoint, and interconnections among various categories are assessed through embedded analyses using the updated IO tables, now grouped into 9 categories. Additionally, earthquake impacts on urban systems are evaluated through comparative analysis. Finally, strategies for energy conservation and emissions reduction are identified.

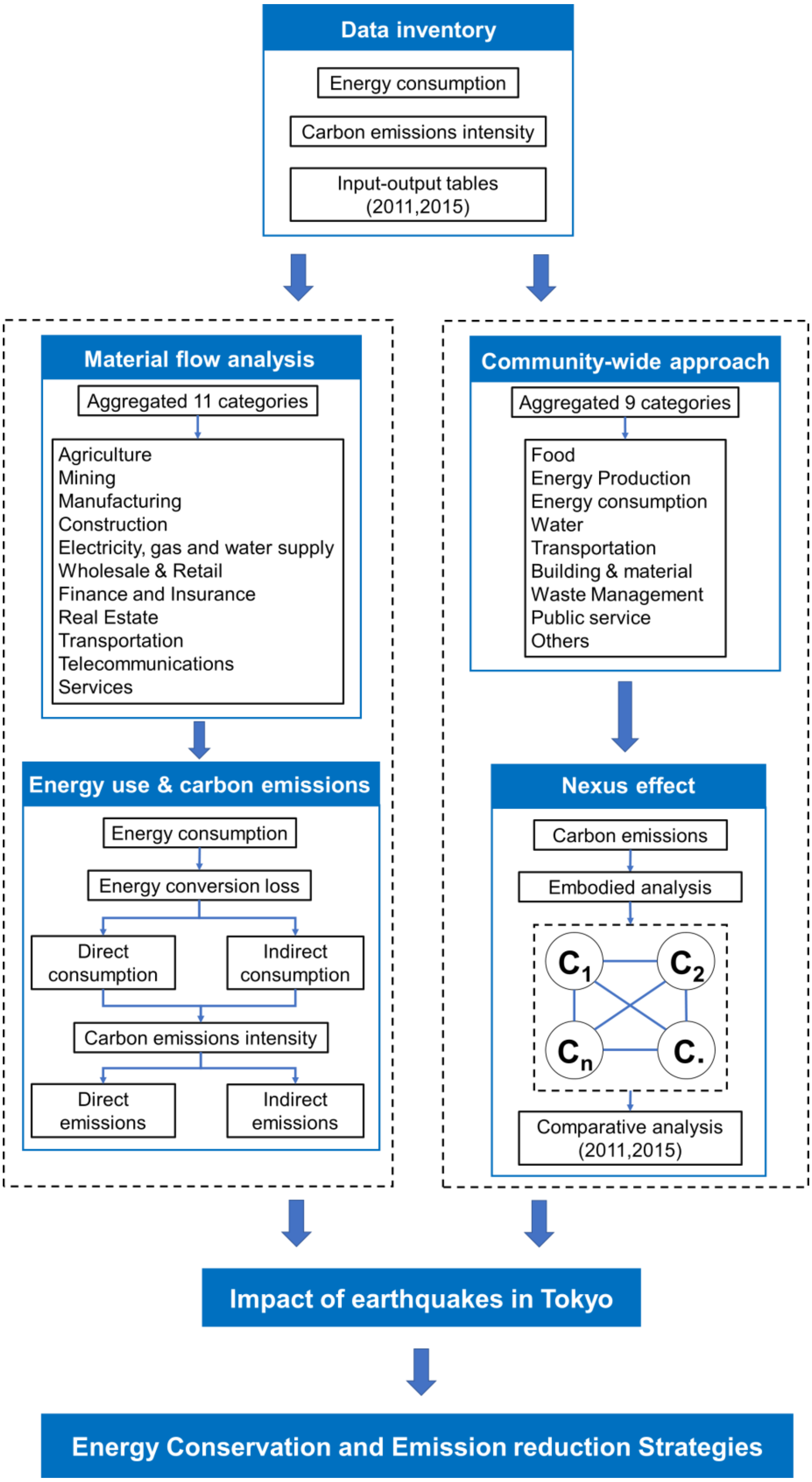

Figure 4.1 Research framework for earthquake

(Figure created by the author.)

4.3.7 Data processing

We used the Tokyo Metropolitan Government Statistics Division's economic IO table with different structures (38 and 191 sectors) for 2011 and 2015, respectively, to assess energy consumption and carbon emissions. The IO tables include intermediate demand, intermediate supply, final demand, imports, gross value added, and total production value. Intermediate sectors include many industries, such as agriculture, mining, and manufacturing. The final demand includes households, the government, and exports. In addition, the IO table is aggregated to a 11-category table, that are Agriculture, Mining, Manufacture, Construction, Electricity, Gas and Water, Wholesale and Retail Trade, Finance and Insurance, Real Estate, Transport and Post, Telecommunications and Service. Energy use and carbon emissions data, including eight types of fuel (i.e., coal, coal products, oil, oil products, natural gas, town gas, electricity, and heat), were gathered from the Agency for Natural Resources and Energy (Agency for Natural Resources and Energy. 2022).

4.4 Carbon emission changes under energy system restructuring

4.4.1 Direct energy consumption and carbon emissions by category in Tokyo

Figure 4.2 depicts changes in direct energy consumption and carbon emissions in different categories in 2011 and 2015. In Figure 4.2(a), the largest proportion of energy is consumed by the service. Energy consumption in the service remains essentially unchanged from 2011 to 2015. Manufacturing was the second most energy-intensive in 2011, and energy use has decreased in these years. In 2015, the electricity, gas, and water supply became the second largest energy consumer. Owing to the impact of the Great East Japan Earthquake in 2011, the electricity power supply was converted from nuclear energy supply to thermal power generation, and the demand for coal was 2.5 times that of 2011.

Direct carbon emissions from various categories in Tokyo can be quantified for six energy sources: coal, coal products, oil, oil products, natural gas, and town gas. In 2011, Tokyo's direct carbon emissions mainly came from petroleum products (48.65%), urban gas (24.58%), and coal (17.98%). In 2015, carbon emissions from coal increased from 17.98% to 31.48%, but petroleum products are still the main contributor to carbon emissions. Figure 4.2 (b) shows that the services was the largest direct carbon emitter in 2011, mainly from oil products and urban gas. Followed by the electricity, gas and water, its direct emissions mostly come from coal. However, owing to the impact of the 2011 earthquake, the electricity, gas and water became the largest direct carbon emitter in 2015, with more than 80% of carbon emissions coming from coal and natural gas. In the electricity, gas and water, carbon emissions from coal in 2015 were 2.5 times that in 2011.

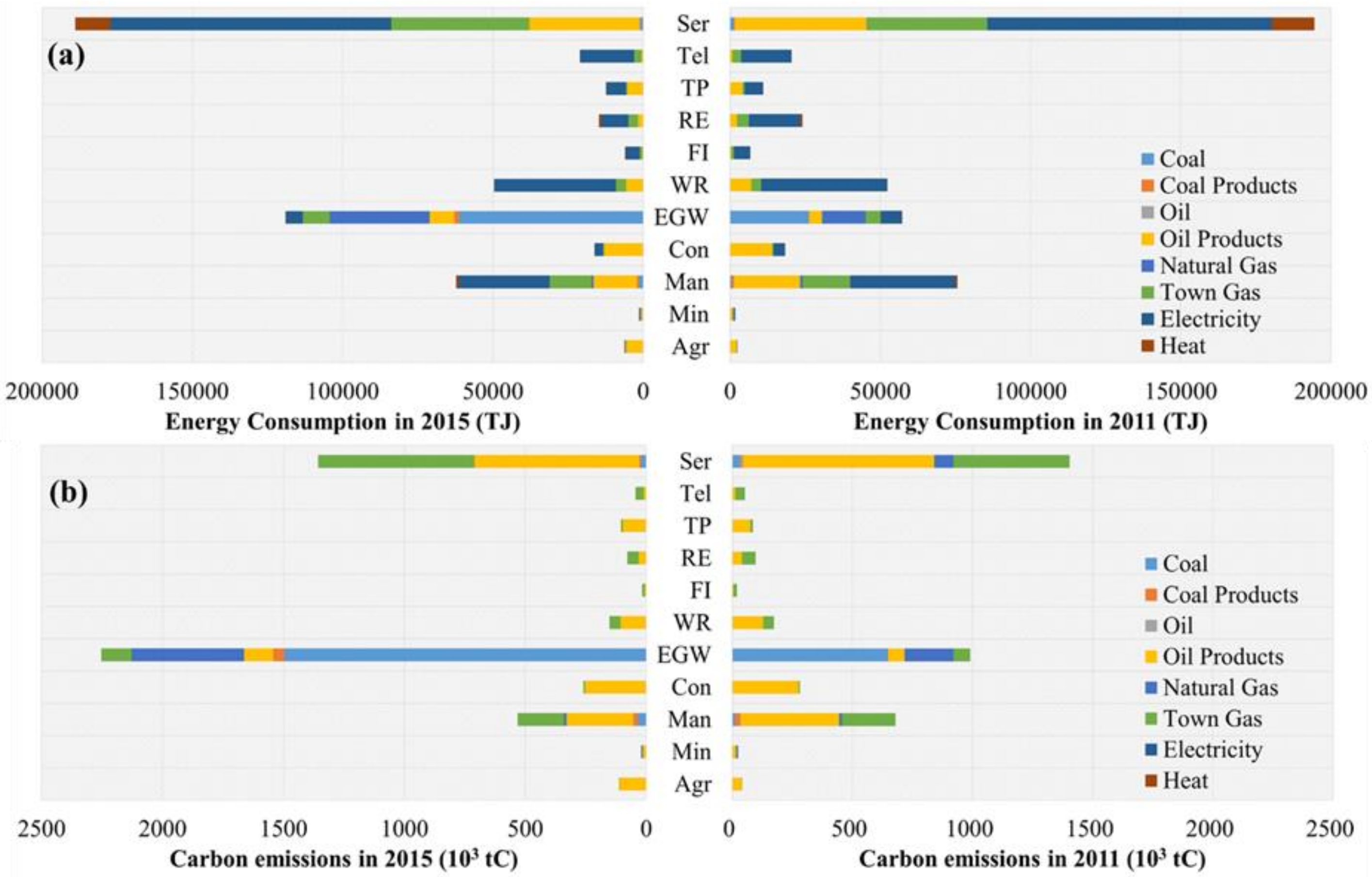

Figure 4.2 Direct energy consumption and carbon emissions in Tokyo

(Figure created by the author.)

Note: Agr, agriculture; Min, mining; Man, manufacture; Con, construction; EGW, electricity, gas and water; WR, wholesale and retail trade; FI, finance and insurance; RE, real estate; TP, transport and post; Tel, telecommunications; Ser, service.

4.4.2 Quantifying carbon emissions from a community-wide approach perspective

Table 4.2 shows the carbon emissions of the nine category and the percentages in 2011 and 2015. Figure 4.3 is a visualization of Table 4.2.

According to the definition of the nine categories in Section 4.3, the definition of the energy category in this study includes energy supply and consumption. The seven categorial emissions of Tokyo accounted for 93.54% in 2011, with food, energy, and water supply accounting for 86.28% (Table 4.2). In 2015, the seven categorial emissions of Tokyo reached 94.9%, with food, energy, and water supply accounting for 88.38%. The growth mainly comes from the energy production. Owing to the impact of the earthquake, carbon emissions from energy production in 2015 were double those of 2011, representing an increase of 1228.9 (103tC).

Table 4.2 Carbon emissions in Tokyo from a community-wide approach perspective

	2011			2015		
	Amount (10^3tC)	Percentage (%)	Cumulative percentage (%)	Amount (10^3tC)	Percentage (%)	Cumulative percentage (%)
F	1282.62	10.66	10.66	1230.19	9.37	9.37
EP	1250.24	10.39	21.05	2479.13	18.88	28.25
EC	7780.44	64.63	85.68	7773.06	59.20	87.45
W	72.09	0.60	86.28	122.18	0.93	88.38
BM	421.23	3.50	89.78	335.53	2.56	90.94
T	211.04	1.75	91.53	273.08	2.08	93.02
WM	143.32	1.19	92.72	144.25	1.10	94.12
PS	98.73	0.82	93.54	98.77	0.75	94.87
Other	777.97	6.46	100	672.96	5.13	100

Note: F, food; EP, energy production; EC, energy consumption; W, water; BM, building and material; T, transportation; WM, waste management; PS, public service.

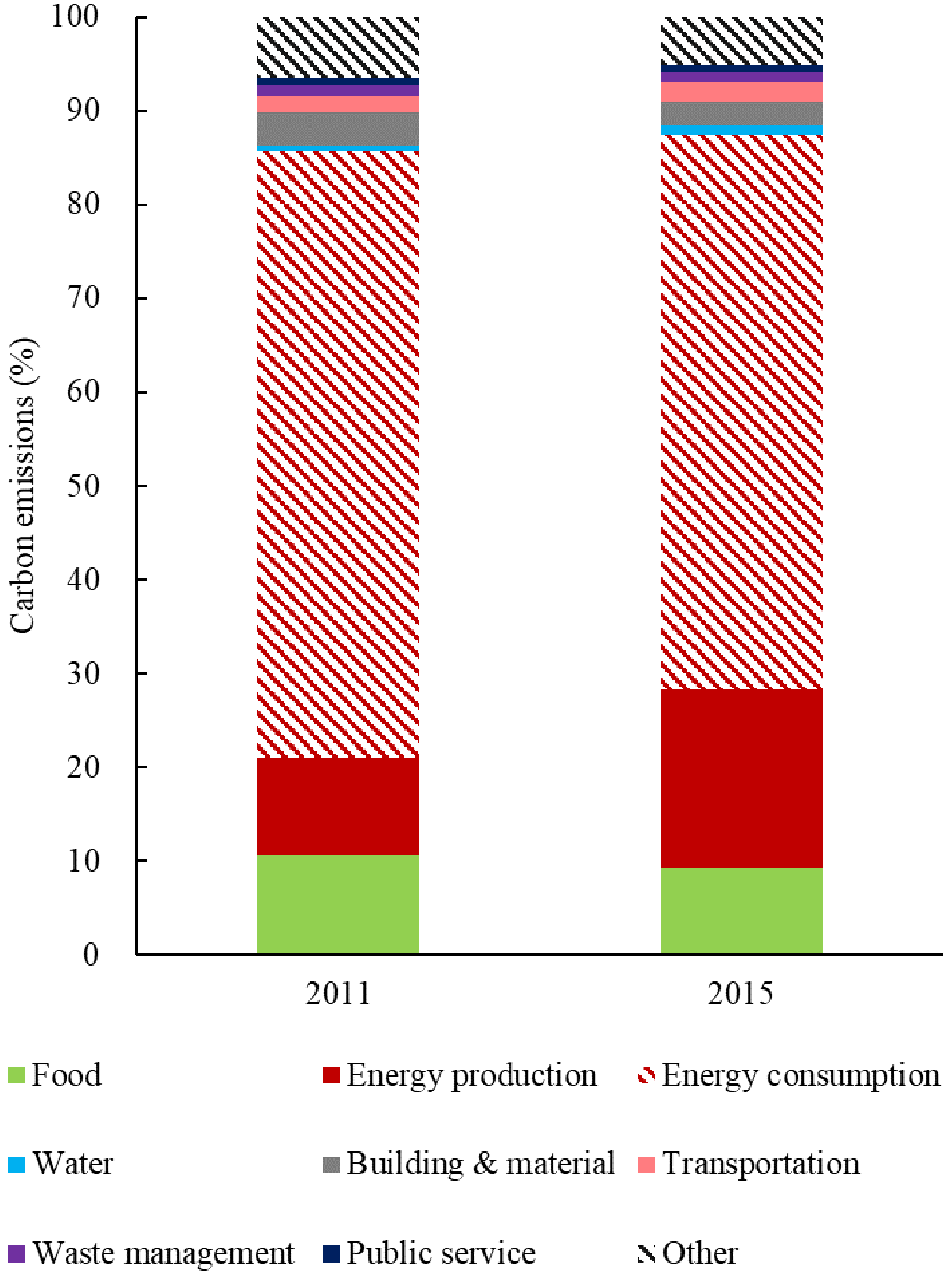

Figure 4.3 Carbon emissions by nine categories in Tokyo
(Figure created by the author.)

Table 4.3 shows the top five embodied carbon emissions exporters and importers in nine categories from 2011 to 2015. As shown in Table 4.3, the main reason for the much higher embodied carbon emissions in 2015 than in 2011 was the change in the city's energy structure owing to the earthquake, which was dominated by thermal power generation. The energy consumption is the largest embodied carbon emissions exporter among the nine with amounts of 2397.23 and 5540.73 (103tC), followed by the energy production, building and material, and transportation. However, owing to its large demand, the category transportation replaced building and material as the third largest embodied carbon emissions exporter in 2015. In 2011, the food and energy production were the top three largest importers of carbon emissions after the energy consumption. However, the transportation and building and material were the top three embodied carbon emission importers in 2015. This case may be related to the extension of the underground line and the refurbishment of facilities around the station.

Table 4.3 Top five embodied carbon emission exporters and importers in nine categories

NO.	**2011**				**2015**			
	Ex	**Am**	**Im**	**Am**	**Ex**	**Am**	**Im**	**Am**
1	EC	2397.23	EC	2388.91	EC	5540.73	EC	3410.30
2	EP	482.38	F	805.42	EP	1097.26	T	1641.77
3	BM	417.28	EP	749.56	T	741.33	BM	1583.34
4	T	407.49	T	507.27	BM	305.12	F	1343.07
5	WM	83.19	BM	409.43	WM	174.96	EP	879.91

Note: Ex, exporter; Im, importer; Am, amount; unit of Am: 10^3tC.

As shown in Table 4.4, for food supply, the food was the biggest embodied carbon consumer among the nine categories, with amounts of 814.49 and 1242.17 (103tC) from 2011 to 2015. The energy consumption was the second largest consumer of embodied carbon emissions, with 40.38 and 49.82 (103tC). In 2015, the food increased embodied carbon input to the building and material.

Table 4.4 Top three embodied carbon emissions in the nine categories

	2011		2015	
Supply	**Consume**	**Amount (10^3tC)**	**Consume**	**Amount (10^3tC)**
F	F	814.49	F	1242.17
	EC	40.38	EC	49.82
	BM	0.89	BM	4.2
EP	EP	1278.42	EP	1885.17
	EC	193.13	T	452.92
	T	124.21	EC	234.22
EC	EC	4744.19	EC	6245.10
	F	564.17	BM	1116.32
	EP	390.46	T	969.03
W	EC	35.05	W	115.48
	F	24.70	EC	40.29
	W	7.58	F	25.63
BM	EC	188.43	BM	961.5
	BM	165.91	EC	84.99
	EP	136.93	PS	70.98
T	EC	215.51	EC	312.83
	EP	54.95	BM	118.52
	F	46.78	EP	50.84
WM	EC	33.60	EC	70.55
	F	24.71	F	56.20
	EP	15.70	EP	20.33
PS	All	0	All	0

For energy supply, the energy production was the biggest embodied carbon consumer from 2011 to 2015, followed by the energy production and transportation. For energy consumption, the energy consumption became the top one embodied carbon consumer. Given that the energy consumption includes manufacturing and services, several manufacturing products are consumed by the service industry. The building and material and transportation were the critical embodied carbon consumers in 2015.

For water supply, the biggest change is that the water became the largest consumer of embodied carbon emissions in 2015 because the earthquake caused changes in the energy supply of water plants. The food was the most important embodied carbon consumer from 2011 to 2015 because of irrigating farmland. For building and materials, investment in public services increased in 2015.

The energy consumption includes several manufactured goods; therefore, the transport of goods led to the energy consumption being the main embodied carbon consumer of transportation. For the waste, the energy consumption, food, and energy production were the top three embodied carbon emissions consumers from 2011 to 2015. Embodied carbon emissions of all categories for public space are 0 because the function of public space is to absorb carbon emissions and reduce the heat island effect.

The biggest changes from 2011 to 2015 have come from the building and material and T. Although direct carbon emissions of the building and material and T are not high in Figure 4.3, these two categories became the main embodied carbon consumer from the EC. They will be an important for achieving urban sustainable development, cleaner production, energy saving, and emission reduction. In addition, the building and material increases public service input to help with the city’s carbon-reduction.

4.5 Indirect carbon emissions and infrastructure rehabilitation

In assessing direct carbon emissions, the configuration of the energy conversion needs to be considered because some high-emitting industries consume considerable energy. However, the energy products of these industries are used by other industries. For example, thermal power generation converts coal and natural gas into electricity, which is heavily used by other industries. These industries should bear the energy losses and carbon emissions generated during the conversion and transmission of electricity. Therefore, this study allocates energy consumption and carbon emissions to categories based on the energy conversion loss to quantify the indirect energy consumption and carbon emissions of each category, thereby reflecting energy use and carbon emissions accurately. The energy conversion losses are expressed in Figure 4.4 as indirect electricity and heat, respectively.

In Figure 4.4(a), the largest proportion of energy consumption is the service. Indirect electricity consumption accounts for more than 30% of total electricity consumption. We find that the service, manufacturing, wholesale and retail, and telecommunications are extremely dependent on electricity. In particular, the indirect electricity consumption of the wholesale and retail trade and Tel exceed 50%.

Calculating indirect carbon emissions from electricity and heat based on energy conversion loss shows that Tokyo's total carbon emissions almost exploded compared with direct emissions. Carbon emissions generated during the conversion and transmission process of electricity supply are the main source of indirect emissions, which also illustrates Tokyo's extremely high dependence on electricity. In terms of the distribution of indirect emissions by category, the service has the largest emissions, followed by the wholesale and retail trade and manufacture.

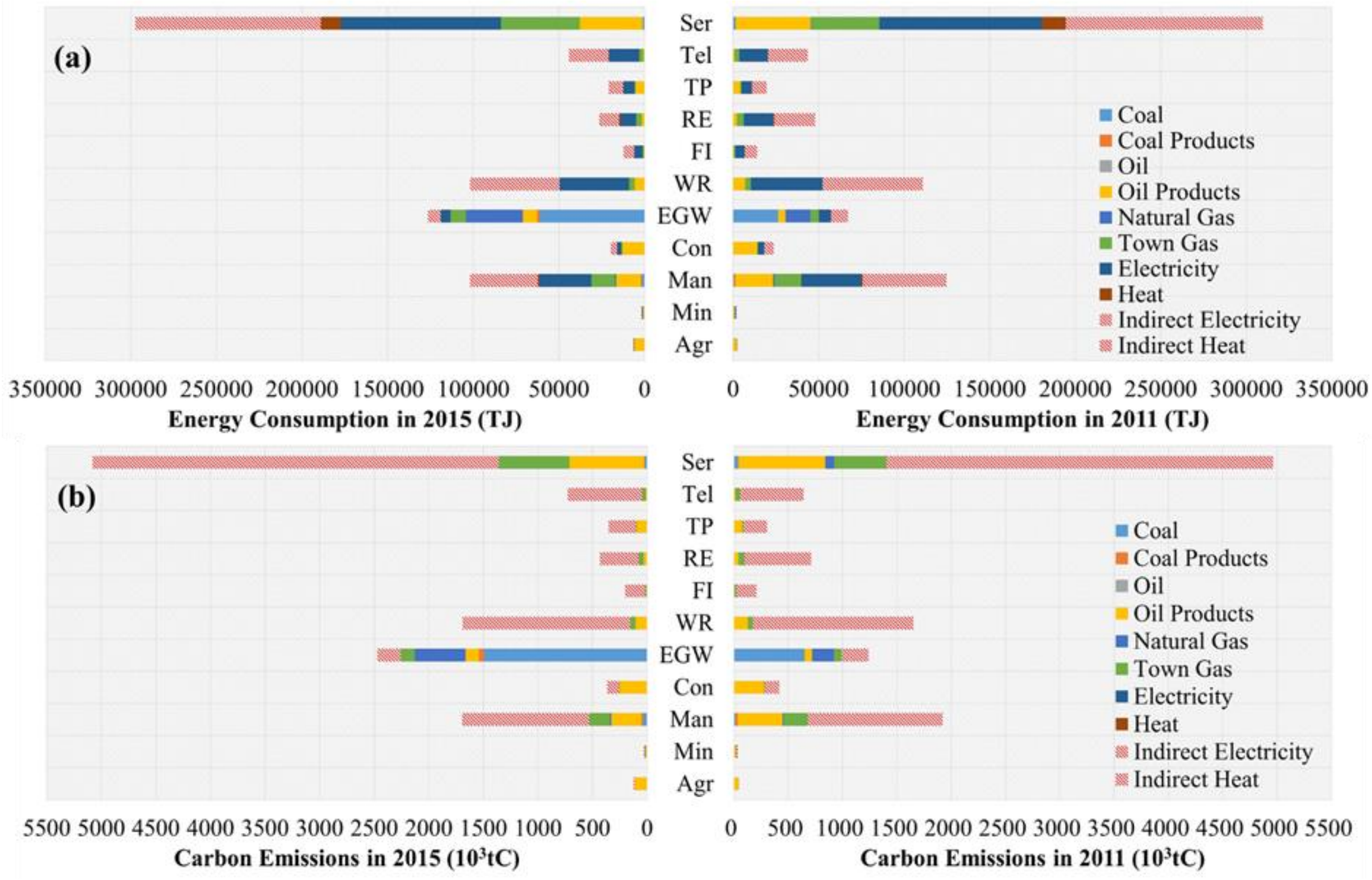

Figure 4.4 Energy consumption and carbon emissions based on the energy contribution loss

(Figure created by the author.)

4.6 Discussion of results: nature and sustainability of earthquake perturbations to pre-existing carbon pathways

4.6.1 Energy consumption and carbon emissions in Tokyo

The results above indicate that although Tokyo maintained economic growth, its energy structure changed because of the Great East Japan Earthquake, leading to increased carbon emissions. Combining Figures 4.2 and Figure 4.4, we find that the electricity category invests considerable coal and natural gas to make up for the loss of power owing to the reduction in nuclear power supply caused by earthquakes. Moreover, the fuel cost of thermal power generation accounts for a higher percentage of the power generation cost than that of nuclear power generation, which in turn leads to an increase in power generation costs owing to soaring fuel costs (The Federation of Electric Power Companies of Japan 2018). The Japanese government is reducing carbon emissions caused by thermal power generation by introducing cutting-edge and efficient thermal power generation equipment and using renewable energy. Japan's main renewable energy sources are solar and wind energy, but the prerequisite for the introduction of renewable energy is to maintain a stable power supply. For example, when renewable energy power generation is large and the power supply exceeds demand, efforts should be made to reduce thermal power and other power generation (The Federation of Electric Power Companies of Japan 2018). As for water consumption, thermal power generation increased because of the shutdown of nuclear power stations after the Great East Japan Earthquake. Thermal power generation required a considerable water for cooling to maintain a steady supply of electricity, resulting in a doubling of water consumption. The Tokyo Waterworks Bureau has been working to reduce energy consumption by replacing existing pumping equipment and lighting with high-efficiency equipment.

Simultaneously, they have been reducing carbon emissions by installing power generation equipment that uses renewable energy sources, such as solar power and small-scale hydroelectric power (T. Tanaka 2018).

An increasing number of education and scientific research, medical services, and various service industries (accommodation, food and beverage, entertainment, etc.) have concentrated in Tokyo, leading to extremely high electricity demand. Considerable high-energy consumption products are consumed for manufacturing production in typical process industries, such as steel, brick and tile, and cement (Xu et al. 2021). Before considering energy losses, Tokyo's direct carbon emissions mainly come from petroleum products and urban natural gas, reaching 3855.44 and 4933.57 (103tC) in 2011 and 2015, respectively. After accounting for energy losses, Tokyo's carbon emissions reached 12132.19 and 13159.38 (103tC) in 2011 and 2015, respectively, representing emissions of 8276.75 and 8225.81 (103tC). In addition, total indirect EC and carbon emissions are higher than direct consumption and emissions. Indirect emissions were 2.1 and 1.6 times higher than direct emissions in 2011 and 2015, respectively. In 2015, direct emissions from the energy category were mainly from coal combustion. If the power conversion efficiency can be further improved and power transmission losses can be reduced, Tokyo's carbon emissions can be greatly alleviated. Services are still the largest consumers of water energy, with the bathing industry consuming the largest amount of water. Therefore, improving the efficiency of electricity and water supply is a key point to reduce energy-use pressures.

4.6.2 Policy implications

In 2015, the building and material category became the second largest consumer of embodied carbon emissions in the energy consumption. Although the building and material contains major raw materials for construction, other raw materials from the energy consumption are still needed. Owing to the impact of the earthquake, the carbon emissions of manufacturing products that rely on electricity production have increased, resulting in the carbon emissions of raw materials for many construction industries also increasing. Considering that most houses in Tokyo are mainly made of wooden materials, the average life expectancy of building structures (22 years) is much shorter than that of houses with cement structures (47 years) (Towa Stage 2018). Therefore, the maintenance and reconstruction of houses will also increase EC and carbon emissions. Based on the experience of the Great East Japan Earthquake, rebuilding Tokyo with advanced disaster prevention functions has become an urgent issue, and efforts are being made to improve areas with densely populated wooden houses. A key objective to minimize consumption and emissions in the building and material should thus be to improve the technology and technical standards of housing construction.

The impact of earthquakes on railway transportation not only led to an increase in direct carbon emissions owing to its high reliance on electricity supply from 2011 to 2015 but also enhanced its earthquake resistance by using products produced from electricity to maintain and repair subway lines (Transportation Policy Review Council 2016). Relieving environmental stress from the T can be effectively accomplished by promoting various policies. In 2010, the Japanese Ministry of Economy, Trade and Industry announced the "Next-Generation Vehicle Strategy 2010," which promoted hybrid electric vehicles and electric vehicles (Maruyama 2014). In addition, the Tokyo government proposed its "Automotive Environmental Management Plan" in 2011, in which companies in Tokyo with a fleet of more than 30 vehicles should replace their traditional cars with low-emission and fuel-efficient vehicles (Bureau of Environment 2018).

For the public space, the Bureau of Urban Development Tokyo Metropolitan Government proposed urban renewal upgrade projects. These projects advance the development of metropolitan government-held land and the surrounding area to enhance urban functions, including industry and disaster reduction, and to boost the vitality and appeal of Tokyo (Bureau of Urban Development Tokyo Metropolitan Government 2015).

4.7 Summary

This study employs a nexus perspective to assess energy consumption and carbon emissions across different categories in Tokyo. Energy consumption and carbon emissions were re-estimated based on the energy contribution loss. Reclassifying the IO table based on the community-wide approach perspective not only allows obtaining the carbon emissions of the nine categories quicker than traditional methods but also to greatly find industrial categories that need energy saving and emission reduction through the correlation among the nine categories. The significant correlation impact among these categories reveals the main paths for formulating energy conservation and carbon-reduction methods. The impact of the earthquake on Tokyo's energy structure and carbon emissions is analyzed by comparing the results of 2011 and 2015.

Through the above analysis, we find that the service is the main source of energy consumption and carbon emissions. There is great potential to conserve energy and reduce carbon emissions in this category, particularly in the catering and public bath industries. Next is manufacturing, which also accounts for a large proportion of Tokyo's energy consumption and carbon emissions. The indirect carbon emissions caused by power supply losses are almost twice as large as direct emissions, how Tokyo optimizes power supply losses is particularly important to achieve a 50% reduction in carbon emissions. In 2015, the transportation and building and material became major importers of embodied carbon emissions, possibly related to earthquakes.

From the above results, we found that emergencies such as natural disasters will greatly affect the energy structure and carbon emission patterns. Particularly after the 2011 earthquake, the energy structure has undergone a very evident shift toward greater use of fossil energy, particularly coal, in response to a significant reduction in the power supply from nuclear power plants, which in turn has led to a significant increase in carbon emissions from the power supply. According to our observations, Tokyo's carbon emission characteristics mainly depend on the service and manufacturing industries in the energy consumption. Following the earthquake, the building and material and transportation categories increased product demand for repair and reconstruction, resulting in a strong correlation between the building and material and transportation sectors and the energy consumption sector in 2015. The impact of increased carbon emissions caused by earthquakes can be mitigated by strengthening the construction of green and public spaces.

While this study reclassifies the IO table from a community perspective, category definitions align with Tokyo's actual conditions, encompassing not just traditional raw materials but also gas, oil appliances, and heating equipment. We recommend tailoring methodologies to local contexts for effective applications. However, data limitations, such as gaps in continuity and reliance on 2011 and 2015 data, hinder comprehensive analysis of pre- and post-earthquake carbon emissions changes. Future work will focus on optimizing data for comparative analysis.

5 Case Study 2: Carbon Emission Characteristics of Online Food Delivery Platform Expansion and Consumption Behavior during the Epidemic

5.1 Chapter introduction

The COVID-19 pandemic and the subsequent lockdown of cities have led to the rapid growth of OFD. Moreover, there are concerns that OFD platforms may impose offers on users in order to continue to increase their market share, leading to numerous environmental issues such as overconsumption and a significant increase in plastic packaging waste. Most studies have focused on the environmental impacts associated with food packaging, and have been mostly limited to China. However, less research has been done on the overall CO_2 emissions of an OFD order including food. In this Chapter 5, the CO_2 emissions of an OFD order were assessed by considering the production, distribution, consumption and disposal of the ingredients, based on lifecycle thinking and existing secondary data, for three representative food groups (Western food, Japanese food and Chinese food) in Japan. This study found that the food production of an OFD order accounts for more than 70% of the CO_2 emissions of the entire process, especially food ingredients production. Policy support and initiatives such as OFD platforms being able to serve different quantities of food based on actual consumer demand to avoid food waste, as well as changes in delivery methods, would help reduce the CO_2 emissions of OFD.

5.2 Review of online food delivery behavior growth trends and platform mechanisms during COVID-19

Explosive growth in the OFD industry has been observed in recent years. Internet platforms allow customers to buy food from partnering restaurants through smartphone applications and have it delivered to their households (Arunan et al. 2021). The rapid uptake of OFD in the last decade has been attributed to factors such as the growth of the internet and e-commerce, hedonic motivation, increasing household discretionary income, and convenience and time-saving in increasingly busier lives (Yeo et al. 2017, Japan's Untapped Food Delivery Market is Already Crowded: Who's Winning?).

The COVID-19 pandemic has accelerated OFD development in Japan over the past two years. According to Measurable AI's e-receipts data, Japan's OFD market share comprises two major companies from 2020 to 2021: Uber Eats (market share over 60%) and Demae-Can (market share about 30%) (Japan's Untapped Food Delivery Market is Already Crowded: Who's Winning?). The OFD industry increased 25% from 2016 to 2020, and it is set to increase by a further 17% from 2021 to 2025 (Food Delivery Service Market in Japan: Key Research Findings 2021).

There have been many studies on OFD in recent years, mainly focusing on obesity (Anderson et al. 2011, Wang et al. 2016, Fraser et al. 2012), cloud kitchens (Choudhary 2019, Belleri 2020), food safety issues (Li 2019), consumption habits (Liu and Chen 2021, Meah and Jackson 2017), social relationships (Ma et al. 2019), and traffic accidents (Yin and Hu 2019, Byun et al. 2020, Zhang et al. 2020). However, the impact of OFD comes from three main areas: economic, social, and environmental.

In social terms, OFD has greatly increased food accessibility, but it has also greatly increased the availability of unhealthy food (Jia et al. 2022). This is because OFD platforms have a large selection of dishes with low nutritional value. OFD provides work opportunities for more people and greatly enhances work flexibility. However, in some countries, couriers have few employment rights and are subject to a dangerous working environment (Ma 2019).

On an economic level, OFD's market revenue was boosted by 27% to US$136.4 billion in 2020 (Online food delivery market to hit $151.5B in revenue and 1.6B users in 2021). Furthermore, the development of OFD brings benefits to many industries, such as the food packaging industry, manufacturing (e-bikes) and sales. However, there have also been some negative effects on the traditional restaurant industry, with many restaurants having to adapt their business models to stay afloat (Li et al. 2020).

Moreover, OFD platforms, through aggressive marketing and promotional strategies, may lead to over-consumption by consumers (Jia et al. 2022). This behavior will greatly increase the burden on waste disposal. As for the environmental impact, the most important point is the generation of large amounts of plastic packaging and how to deal with it (Li et al. 2020). For example, the amount of waste from OFD packaging in China increased by 650% in 2017 compared to 2015 levels (Song et al. 2018). In 2020, influenced by the COVID-19 pandemic, consumers preferred single-use plastic packaging, which in turn led to a rapid growth in plastic packaging waste (Li et al. 2020).

Another important environmental issue is CO_2 emissions associated with OFD. The main sources of environmental impact (solid waste pollution, water pollution, resource consumption, and air pollution) are production and waste disposal along the whole industry chain of OFD packaging (Wen et al. 2019).

Since the OFD industry is relatively young, research and discourse on OFD and its environmental effects is limited. In addition, many studies have focused on China, as OFD was growing rapidly before the COVID-19 pandemic. Meanwhile, due to the impact of the pandemic, the OFD industry has grown rapidly in Japan. Meals from restaurants/fast food chains will be the next increase in OFD over the next five years (Japan's Untapped Food Delivery Market is Already Crowded: Who's Winning?, Food Delivery Service Market in Japan: Key Research Findings 2021). This makes OFD research in Japan a new academic hotspot.

Relevant literature and main findings on CO_2 emissions from OFD and on consumer behavior have been reviewed as follows:

The increase in OFD will affect all stages of the food supply chain and have more serious environmental issues. Significant CO_2 emissions have occurred from food packaging production, food delivery, and waste generation (Li et al. 2020, Yi et al. 2017). Two thirds of packaging demand come from the food industry, such as food containers, cutlery, napkins, and plastic bags, which will lead to resource depletion and large CO_2 emissions due to the high demand for energy and raw materials (Li et al. 2020). These materials are frequently single-use, necessitating huge amounts of energy and raw materials to manufacture, transport, and dispose of them. Packaging production and disposal can also lead to the release of a wide range of pollutants into the environment (Fan et al. 2017). All of this points to OFD catalyzing the increasing consumption of packaging-derived plastics, which already account for 46% of worldwide plastic waste.

Research on OFD has mainly focused on CO_2 emissions related to different OFD product packaging processes from production to waste treatment (Arunan et al. 2021, Zhang et al. 2022) and CO_2 emissions related to OFD waste disposal (Zhang and Wen 2022). For example, Arunan et al. (2021) quantified the packaging-related greenhouse gas emissions associated with OFD's orders in Australia. Packaging raw materials contribute at least 50%. As the OFD industry continues to grow, CO_2 emissions associated with OFD packaging are expected to increase by 132% by 2024. Liu et al. (2020) found that OFD waste is a small proportion of municipal solid waste, however, food packaging waste accounts for 15.7% of the total. Plastic bags were the most used packaging at 35% and plastic boxes accounted for 27%. However, the environmental impact of paper boxes cannot be ignored. Despite their lower usage, the environmental impact potential of NOx generated during the production of paper boxes far exceeds that of CO_2.

Camps-Posino et al. (2021) assessed the impact of OFD's packaging and its waste disposal on climate change based on LCA and explored the advantages of increasing recycling rates, the amount of packaging recycled and the use of reusable packaging. This study found that takeaway packaging in China emits approximately 13 million tons of CO_2. If the recycling rate is increased to 35%, packaging emissions would be reduced by 16%. If packaging made from recyclable materials is increased by 50%, emissions would be reduced by 60%. In addition, if reusable packaging is used, emissions would be reduced by 63%.

Zhang et al. (2022) combined the direct weighing method with a questionnaire to analyze the scale, pattern and impact of OFD waste. This research found that the total amount of OFD waste in 2019 was 177.6 kilotons, CO_2 emissions were 168.3 kilotons and packaging waste accounted for 32%. Significant differences in OFD waste were found between different consumer groups, with white-collar workers contributing the highest amount at 58%. This could be reduced by 25% if waste-to-energy technologies were implemented as planned, and by 55% if the avoidable portion of OFD waste was avoided.

Some researchers found that recycling these packages could significantly ease energy consumption for production, thereby reducing CO_2 emissions (Yi et al. 2017, Vitale et al. 2018). In Australia, some food companies offer reusable food containers (stainless-steel containers), greatly enhancing the sustainability of food packaging (Arunan et al. 2021).

The impact of consumer behavior on OFD comes from two main components: purchasing behavior and selection of disposal of OFD waste.

For consumers, there is no doubt that selecting OFD can save them a great deal of time. In China, each OFD order can save consumers at least 48 minutes (Li et al. 2020). Studies have also shown that OFD produces less food waste than eating at home, because home cooking sometimes has led to an increase in food waste by producing more food than household demand (Evans 2012). The relatively small size of the portion, due to the limitations of the container, makes it easier for consumers to finish their meal. Furthermore, CO_2 emissions from the production and preparation of different foods are different. For example, in Japan, a study found that Western food has higher CO_2 emissions than Chinese food or Japanese food in the household (Inaba et al. 2014). So, from an environmental point of view, the kind of food that consumers choose determines the carbon footprint of OFD at the production stage, and selecting OFD can reduce a certain amount of food waste.

Consumer attitudes are an important factor in evaluating the environmental impact of the food supply chain, particularly in waste disposal and recycling (Mancini et al. 2017). Some studies have found that changes in consumer behavior at the waste disposal stage can significantly reduce CO_2 emissions (Vasileva and Ivanova 2014). Despite consumers' environmental awareness, most people are unaware of how food waste is generated, and do not know about recooking leftovers and reusing meal containers (Liu and Chen 2021). For example, in Changchun, China, more than half of university students do not separate leftover food from its container when they dispose of such waste. The main reason for this is a lack of knowledge about waste separation (Qiu et al. 2019). While there are many factors that influence consumer sorting behavior, such as age, gender, education level, income level and the uneven distribution of waste facilities (Cichocka et al. 2020), for those consumers who are not interested in recycling, inconvenience of disposal and recycling is the main reason (Arunan et al. 2021).

Current research on the CO_2 emissions of OFD has focused on the CO_2 emissions of OFD-related packaging from production to disposal, and researchers have found that the production of packaging raw materials accounts for at least 50% of the entire process. However, due to the complexity and limitations of the food data, most studies do not consider the contribution of food ingredients in the CO_2 emissions of OFD. Moreover, distribution, an important part of OFD, is not addressed in many studies. Based on secondary data, this study analyses the CO_2 emissions of OFD from three different food groups (Western food, Japanese food, and Chinese food) in Japan, taking food production in particular into account.

Existing studies have only focused on CO_2 emissions from OFD-related packaging and have not considered the CO_2 emissions of food production and distribution. This chapter considered Western food, Japanese food, and Chinese food as three representative OFD food groups, and developed a framework to estimate the overall greenhouse gas emissions of an OFD order through its entire process by considering the production, distribution, consumption and disposal of the food ingredients and related plastics, based on lifecycle thinking and existing secondary data in Japan. Through scenario analysis, the framework not only compares the impact of the three different food groups on the CO_2 emissions of OFD, but also calculates how much different distribution methods and disposal methods contribute to CO_2 emissions generated by OFD. Furthermore, policy recommendations to prevent and reduce CO_2 emissions are provided based on a scenario analysis.

5.3 Materials and methods

5.3.1. Scope and unit definition

The scope of this research is to assess the environmental impact of OFD. As shown in Figure 1, this study divides the environmental impact of OFD into four components: production, distribution, consumption and end of life/recycling. The environmental impact indicators for assessing OFD mainly consider CO_2 emissions and waste volumes. For this research, the functional unit is defined as a single packaged online food for one person.

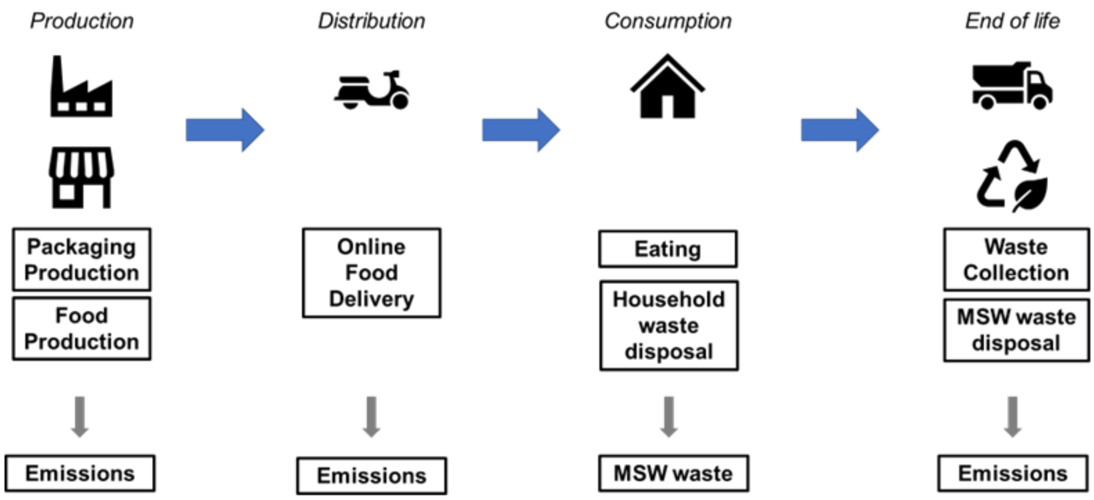

Figure 5.1 System boundaries
(Figure created by the author.)

5.3.2. Calculation framework

Figure 5.2 shows the calculation framework for OFD consisting of the production stage, distribution stage, consumption stage, and waste disposal stage. The red rectangle represents the target, the green rectangle represents the calculation process and the dotted line represents no data. The production stage not only covers food ingredients production and OFD container production, but also covers cooking in restaurants. Distribution comprises a wide range of transport options, such as cycling, motorized bicycle, motorbike, and other vehicles. Waste disposal considers not only waste collection and transportation but also land-fill and incineration.

The framework analyses the environmental impacts of different OFD and the impacts of different consumer behaviors on OFD. Firstly, the contribution of CO_2 emissions at different LCA stages of different OFD is analyzed. Secondly, the environmental impacts associated with consumer decisions on OFD purchase, consumption, and disposal are analyzed.

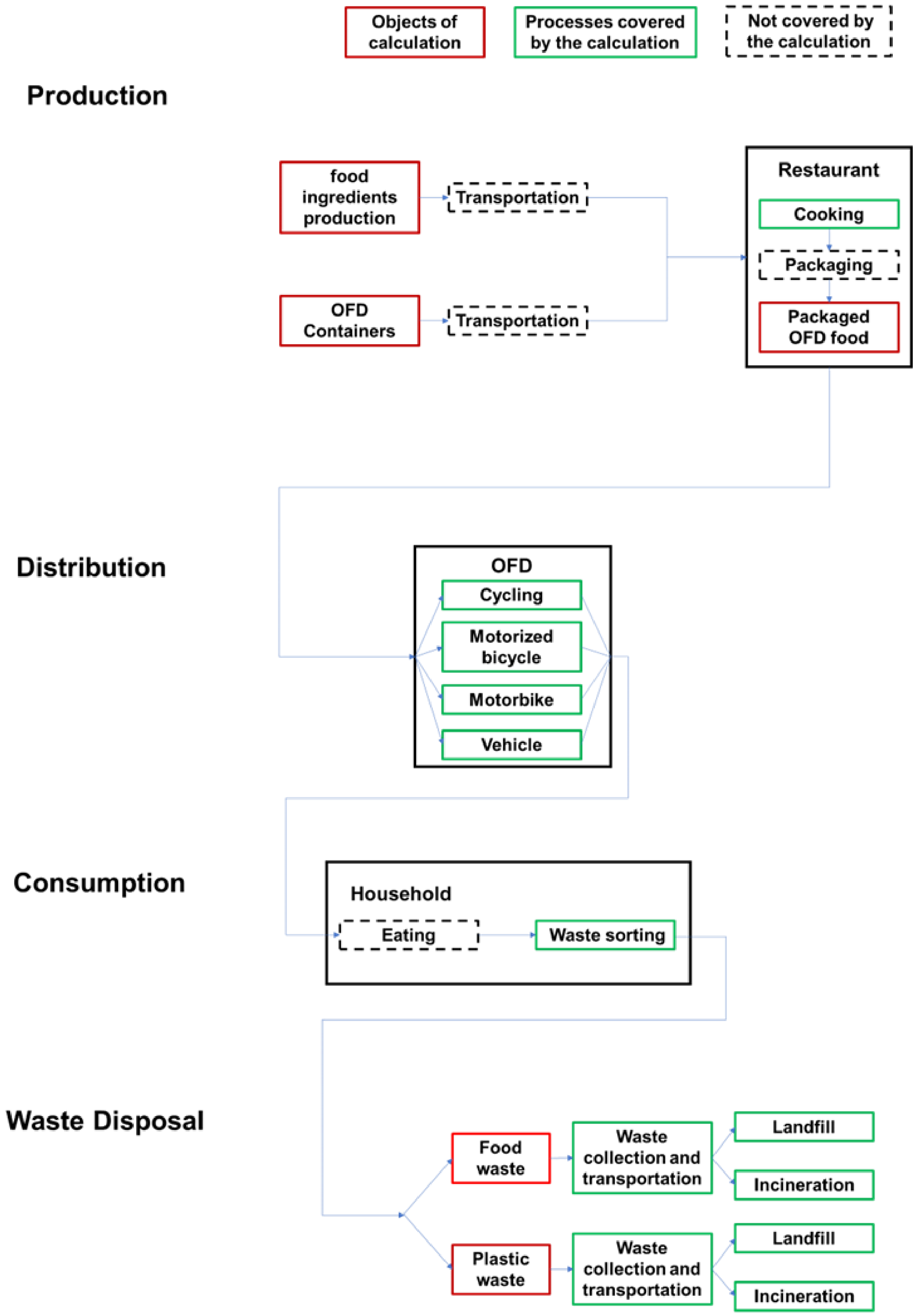

Figure 5.2 Calculation framework
(Figure created by the author.)

5.3.3. Databases

5.3.3.1. Food production

In this research, food production includes food ingredients production and cooking in restaurants. Table 5.1 shows the CO_2 emissions generated by food ingredients production and household cooking of three types of food, where food ingredients production includes the processes of ingredient production, packaging, and transportation (Inaba et al. 2014). CO_2 emissions from restaurants are 1.2 to 1.8 times higher than household emissions, averaging 1.5 times (Inaba et al. 2014). Table 5.2 shows LCA progress of CO_2 emissions generated by food cooking in restaurants.

Table 5.1 CO_2 emissions of food production in households

Food types	**Materials**	**CO_2 of food ingredients production (kg-CO_2/per meal)**	**CO_2 of food cooking (kg-CO_2/per meal)**
Western food	Bread	0.04303	0.00770
	Hamburg steak	1.12801	0.04911
	Potato salad	0.10577	0.03484
	Vegetable soup	0.11105	0.01177
Japanese food	Rice	0.04734	0.02012
	Tempura	0.38877	0.00011
	Pickles	0.10921	0.00000
	Miso soup	0.05581	0.01177
Chinese food	Rice	0.04734	0.02012
	Dumplings	0.17401	0.01705
	Fried vegetables	0.24929	0.01783
	Chinese soup	0.15694	0.01177

Table 5.2 Total CO_2 emissions of food production in households and restaurants

Food types	CO_2 emissions in households (kg-CO_2/per meal)	CO_2 emissions in restaurants (kg-CO_2/per meal)
Western food	1.491	2.236
Japanese food	0.633	1.010
Chinese food	0.694	1.041

5.3.3.2. Food weight

Based on previous studies (Tsuda et al. 2006, Tsuda et al. 2007), the weight of the different components was measured. Compared to Western and Japanese food, Chinese food is the heaviest. This is because the raw materials for Chinese soup come mainly from large amounts of chicken and water, whereas Western soups are based on small amounts of vegetables and milk. As shown in Table 5.3, compared with Western food and Japanese food, the containers for Chinese food are complex.

Table 5.3 Weight of three food types

Food types	Materials	Weight (kg)	Images
Western food	Total	0.585	
	Bread	0.06	
	Hamburg steak	0.289	
	Potato salad	0.129	
	Vegetable soup	0.108	
Japanese food	Total	0.750	
	Rice	0.100	
	Tempura	0.359	
	Pickles	0.030	
	Miso soup	0.261	
Chinese food	Total	0.885	

Rice	0.100	
Dumplings	0.060	
Fried vegetables	0.324	
Chinese soup	0.401	

5.3.3.3. Container production

We obtained some common materials and weights of OFD containers from a website (Packstyle 2023) (Table 5.4). The selection of container styles is based on the images in Table 5.3.

Table 5.4 Weight of container

Food types	**Materials**	**Weight (kg)**
Japanese food	PSP	0.007
	PSP	0.005
	PSP	0.005
	PP	0.005
Western food	PSP	0.015
	PSP	0.005
	PP	0.005
Chinese food	PSP	0.005
	PP	0.005

(PP: Polypropylene, PSP: polystyrene paper)

This study sets out CO_2 emissions from containers made of different materials (Table 5.5) (Plastic Recycling and Use Association 2019). For environmentally friendly materials (Bio-PE, PLA, PHBH), CO_2 emissions data from the manufacturing process are not available and are not considered in this study.

Table 5.5 CO_2 emissions from container material

Materials	CO_2 intensity in production process (kg-CO_2/kg)	CO_2 intensity in manufacturing process (kg-CO_2/kg)	Total CO_2 intensity (kg-CO_2/kg)
PSP	2.695	0.56	3.255
PP	1.52	1.013	2.533

5.3.3.4. Distribution of online food delivery

A survey conducted by Tokyo Smart Restaurant LLC in 2022 of 1,013 takeaways found that delivery was mainly done using bicycles, motorized bicycles, motorbikes, and vehicles (Nearly 40% complain that orders are hard to get! 2023). Table 5.6 shows the CO_2 emissions from OFD's main distribution (Matsuhashi et al. 2004). Within the framework of the system that we designed (Figure 5.2), the distribution of OFD is only considered from the restaurant to the home, and the main CO_2 emissions from this process are mainly from energy consumption.

Table 5.6 CO_2 emissions of distribution.

Types	CO_2 emissions (kg-CO_2/person・km)
Cycling	0
Motorized bicycle	0.031
Motorbike	0.092
Vehicle	0.190

5.3.3.5. Waste disposal

According to IDEA database, this study establishes waste disposal database (Table 5.7). It includes landfill services, and incineration services without power generation.

Table 5.7 CO_2 emissions of waste treatment

IDEA Product Code	Product Name	Unit	kg-CO_2
851611201	Landfill treatment service, domestic waste, waste plastics	kg	0.0357
851611202	Landfill treatment service, domestic waste, kitchen garbage	kg	0.0628
851612000	Incineration service, domestic waste	kg	0.9751
851612201	Incineration service, domestic waste, waste plastics	kg	2.9745

5.3.4. Impact assessment

5.3.4.1. Quantifying CO_2 emissions from packaging production

Combining Table 5.4 and Table 5.5, the environmental impacts of food packaging were estimated. CO_2 emissions generated from OFD package in the production progress can be calculated using Eq (1):

$$C_p = O_p \times W_{po} \tag{1}$$

Where C_p is the CO_2 emissions from production food packaging; O_p is the carbon intensities, W_{po} is the weight of the food package per order.

5.3.4.2. Quantifying CO_2 emissions from distribution

If we want to quantify the CO_2 emissions related to deliveries made from restaurant to household, we need to consider two important factors: the type of delivery, and the distance from the restaurant to the household. According to the Demae-Can website, we can find that the average delivery distance is 1.7 km (Demaecan 2023). Therefore, according to Table 5.6, we can calculate CO_2 emissions for different types of OFD.

5.3.4.3. Quantifying the CO_2 emissions of waste treatment

The annual CO_2 emissions from waste treatment of OFD package waste can be calculated using Eq (2)–(3) (Heard et al. 2019):

$$C_{ct} = W_{po} \times c_{ct} \quad (2)$$

$$C_{wt} = W_{po} \times c_{wt} \quad (3)$$

Where C_{ct} is the total CO_2 emissions of waste collection and transportation kg CO_2; C_{wt} is the total CO_2 emissions of OFD waste treatment kg CO_2; c_{ct} is the GHG emissions intensity of waste collection and transportation kg CO_2/kg; c_{wt} is the GHG emissions intensity of waste treatment kg CO_2/kg.5.3 Life Cycle Carbon Emission Analysis under Food Category Differences.

5.3.5. Scenario analysis

Consumers' dietary choices and waste disposal will largely influence the environmental impact of OFD. As a result, scenario analysis is used to conduct a test in the framework's last section under diverse consumer behavior patterns. The frameworks of scenarios representing various customer behavior patterns are shown in Figure 3. Food and packaging selection, distribution, distance, food waste, packaging disposal, trash transportation, and plastic treatment make up the seven-step pattern investigated.

Combinations of patterns from the nine stages are used to illustrate the scenarios. An 8-digit number is used to identify each food product situation. Each digit in the scenario's nomenclature corresponds to a pattern in eight of the nine stages, excluding packaging disposal patterns. For example, one scenario is designated as "12321142" when food selection is western food (pattern10000000), packaging is PP (pattern1000000), distribution is by motorbike (pattern 300000), distance is 1-2 km (pattern 20000), food waste is 0 (pattern 1000), the weight of the soup is ignored, waste transportation is pattern 100, food disposal is not needed (pattern 30), and plastic disposal is by incineration (pattern 2). Waste treatment is determined by the consumer when they dispose of the food waste and packaging. Due to the lack of recycling data, this model calculation only considers landfill and incineration.

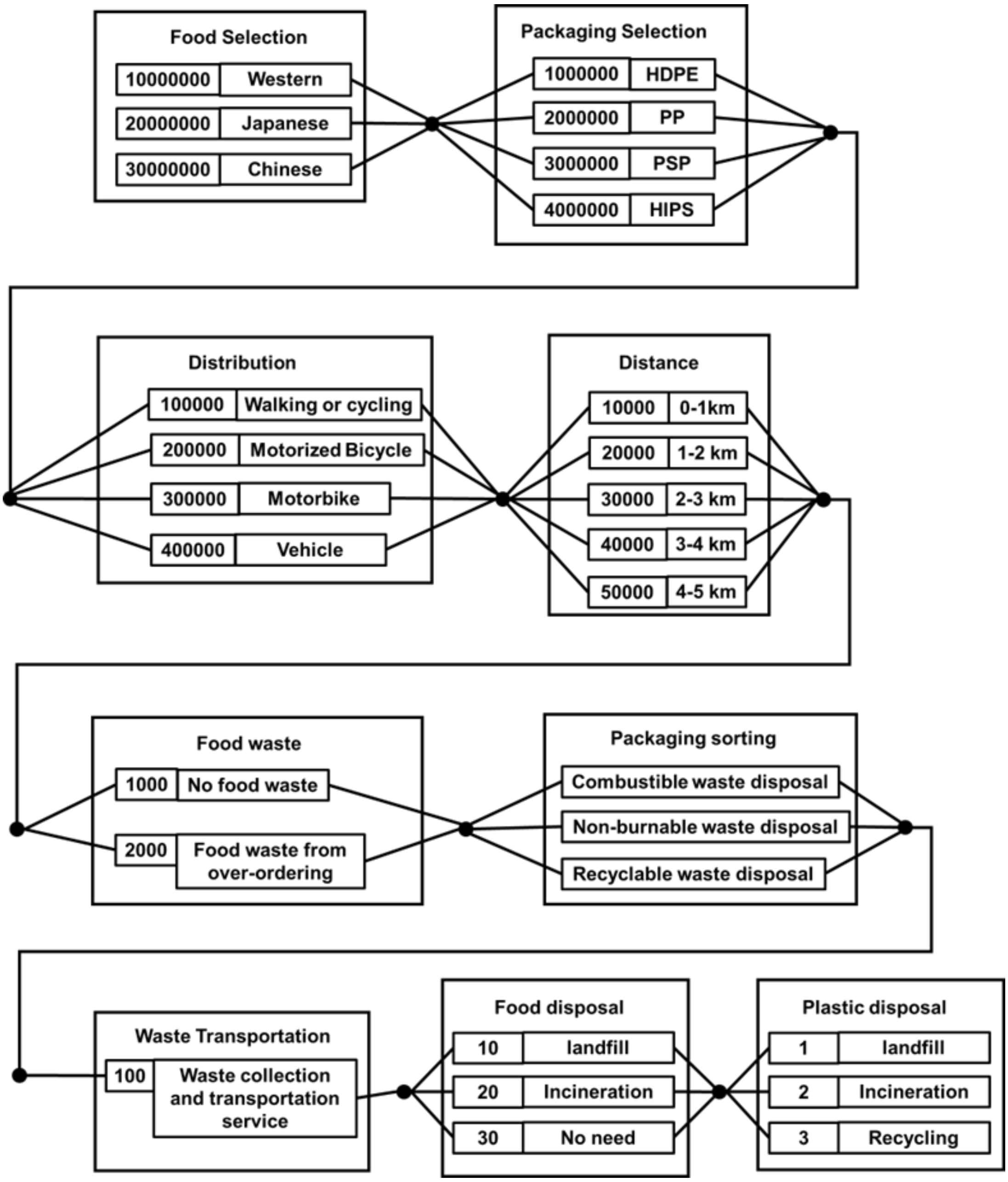

Figure 5.3 Scenario analysis from food selection to plastic disposal.
(Figure created by the author.)

5.4 Carbon emission reduction potential and rebound risk in changing consumption structure

5.4.1. CO_2 emissions from online food delivery

Figure 5.4 shows the CO_2 emissions from three typical OFD foods. The selection of food and plastic containers is determined by the actual situation. According to the questionnaire on the Iideli website (Iideli 2023), during the COVID-19 pandemic, 69.7% of takeaways chose motorbikes, so distribution chose motorbikes. According to the Demae-Can website, the average delivery distance is 1.7 km (Demaecan 2023). Because the functional unit was set up as a one-person takeaway, we assumed that the consumer ate all the food and did not produce any food waste. According to a report by Fundamentals of Plastics Recycling (Plastic Recycling and Utilisation Association 2023), 79.5% of municipal waste (including plastic waste) is incinerated, so plastic waste is incinerated.

We can find that Western food has the highest CO_2 emissions, followed by Chinese and Japanese foods. Food production accounts for 87.9%, 77.7% and 72.7% of the total CO_2 emissions, respectively. On the other hand, plastic container production only accounts for 3.1%, 5.2% and 8.1% of the total emissions, and all CO_2 emissions related to plastic, including plastic manufacturing, production of plastic containers, plastic waste collection and transportation, and disposal of waste, account for 6.0%, 10.3% and 16.4% of total emissions, respectively. Therefore, it has been found that food production has a significant impact on CO_2 emissions generated by OFD. On the other hand, providing a choice of the material used for OFD containers does not have a significant environmental impact on OFD since the total weight per meal is not high.

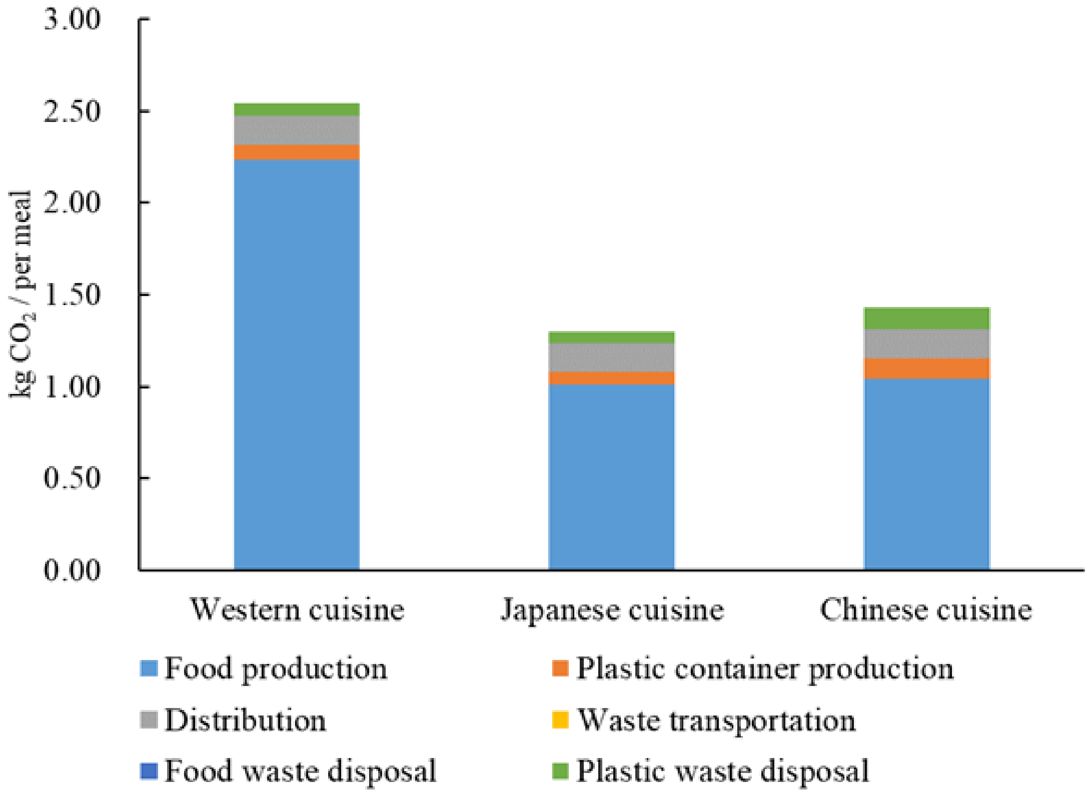

Figure 5.4 CO_2 emissions from three typical OFD foods
(Figure created by the author.)

5.4.2. The CO_2 emissions of distributions

Figure 5.5 illustrates the best, average and worst scenarios for CO_2 emissions from OFD in Japanese food. According to a report by Japan Food Delivery Company (Bento delivery service survey 2023), the most popular OFD food is Japanese food, accounting for 88%, so the food selection is Japanese food. The material used for food packaging, depending on the actual situation, is HIPS. Due to the hilly terrain in Japan, OFD cannot rely entirely on bicycle delivery. Therefore, the appropriate distribution method is chosen for different areas and distances. When making the calculation, we roughly assume 0–2 km by cycling, 2–4 km with motorized bicycles or motorbikes, and over 4 km with motorbikes or other vehicles. Therefore, the best scenario is to choose cycling for a distance of 0–1 km. General conditions would be a motorbike and 1.7 km. According to the Demae-Can app, the maximum distance found for OFD is about 5 km (Demaecan 2023). The selection of food waste, packaging disposal, waste transportation, food treatment, and plastic treatment give the same results as 3.1.

With different conditions in each scenario, the distribution stage contributes from 0% to 45.4% of the total amount of CO_2 emissions. Cycling delivery does not generate any CO_2 emissions. However, when the customer lives far from the restaurant and gasoline vehicles are needed for delivery, there is a sudden increase in CO_2 emissions for the distribution stage. Although the environmental impact of OFD distribution can be small or large, the share of vehicle distribution in Japan is only 3.6%, with 94.7% of distribution coming from bicycles and motorbikes. Overall, the environmental impact of OFD distribution ranges from 0 to 12.0%.

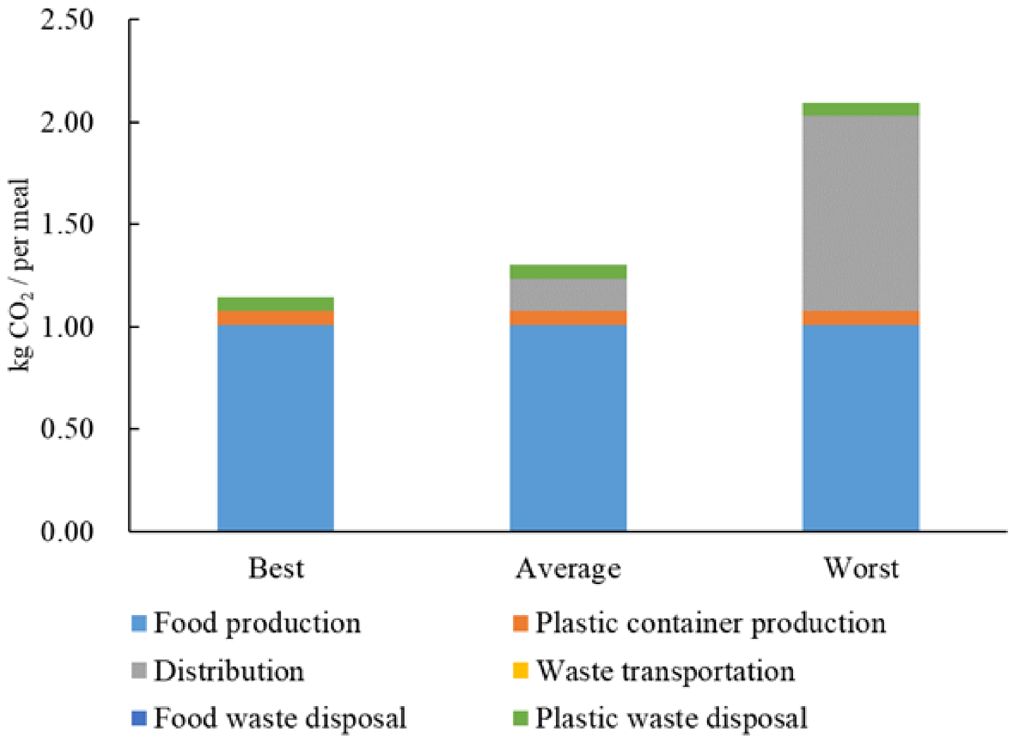

Figure 5.5 CO_2 emissions from different types of distribution for Japanese food
(Figure created by the author.)

5.5 Institutionalization possibilities of platform governance and policy guidance

5.5.1. Over-ordering

The results of this study are based on Japanese Food Guide Spinning Top for food intake per person per meal (Ministry of Health, Labour and Welfare 2023). However, many businesses on OFD platforms set minimum spending amounts, resulting in consumers having to buy 1.5–2 times more food than they need. Therefore, Figure 6 is based on the scenario design of result 4.1 and adds a second salad, tempura, and dumplings to the Western, Japanese, and Chinese meals respectively to meet the minimum spending amount. However, for health reasons, the extra food (second salad, tempura, and dumplings) is not eaten and ends up being disposed of as food waste. According to the latest Japan Waste Disposal Report published by the Ministry of the Environment, Japan (Japan Waste Disposal Report 2023), 224 out of 1741 municipalities collected food waste separately from burnable waste, which means the remaining 1517 municipalities put food waste into incineration facilities together with burnable waste. Therefore, incineration has been chosen for food waste disposal.

Figure 5.6 shows the excess CO_2 emissions triggered by the increase in food leftovers due to over-ordering at different stages of OFD. We have found that additional food led to an increase of 16%, 72%, and 28% in the total CO_2 emissions of OFD for Western food, Japanese food, and Chinese food, respectively. Meanwhile, over-ordering food leads to an increase in CO_2 emissions at different stages of OFD, especially food waste disposal. Taking Japanese food as an example, the second serving of tempura leads to an increase in CO_2 emissions of 52%, 43%, 62%, and 45% in food production, plastic production, waste transportation, and plastic waste disposal, respectively. For food waste disposal, CO_2 emissions increased from 0 to 15.7% of total emissions. Therefore, food leftovers due to over-ordering have a significant impact on the CO_2 emissions of OFD.

Food wastage as a result of OFD is frequently associated with the "minimum price" set by restaurants on OFD platforms, which results in users buying more food than they need to satisfy the "minimum price" of the free delivery service (Liu and Chen 2021). This pattern of minimum prices leads to the creation of leftovers. The inability to preserve leftovers in a timely manner or the reluctance of consumers to preserve them leads on the one hand to an increase in food waste, visible to the consumer, and on the other hand to an increase in CO_2 emissions due to over-ordering, especially at the waste collection and disposal stage, which is a part of the impact that is invisible to the consumer. If OFD platforms could offer different food options to meet the different needs of a wide variety of consumers, it would not only reduce food waste but also significantly reduce CO_2 emissions.

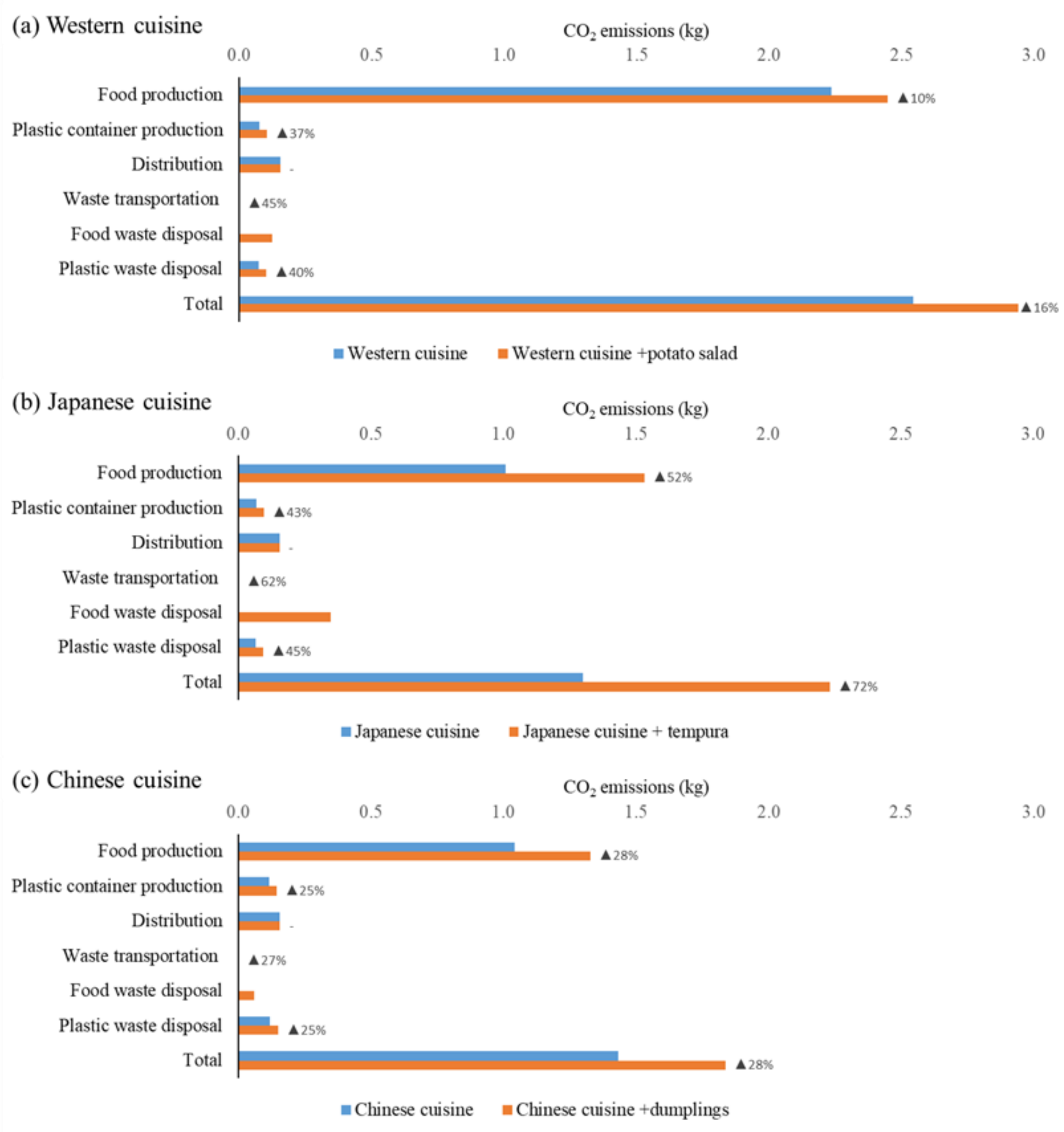

Figure 5.6 Differences in CO_2 emissions from OFD by over-ordering
(Figure created by the author.)

5.5.2. Shifting the distribution

Although the environmental impact of distribution for each order is not high, the question remains as to whether the environmental impact of distribution for OFD is also not significant at urban or national scales due to the increasing demand. According to public data, we discovered that the total number of orders in 2019 on Demae-Can was

3.25 million orders and the current share of delivery methods was as follows: bicycle (25%), motorbike (69.7%), vehicle (3.6%) and other (3.6%) (Demaecan 2023).

Therefore, we have simply estimated the environmental impact of Demae-Can's distribution at the national scale in 2019 (Figure 5.7). The original pattern is the total CO_2 emissions of Demae-Can's distribution in 2019 with a delivery distance of 1.7 km (Demaecan 2023). S1 pattern replaces 50% of motorcycles with motorized bicycles while keeping everything else unchanged. S2 pattern replaces all motorcycles with motorized bicycles and replaces all cars with motorcycles.

Figure 5.7 indicates that CO_2 emissions from OFD can be reduced by shifting delivery method from high-emitting transportation to low-emitting transportation. When shifting from the original pattern to the S1 pattern, CO_2 emissions are reduced by 29.96%, while shifting from the original pattern to the S2 pattern, CO_2 emissions dropped by 64.89%, suggesting that a change in OFD distribution can contribute significantly to regional emissions reductions. Obviously, the best choice for OFD delivery is cycling for a short distance, followed by motorized bicycles for a relatively short distance. Thus, reconsidering the business area of the restaurants from a delivery perspective will make a significant contribution to reducing CO_2 emissions. Moreover, a single OFD delivery to fulfill multiple orders will significantly alleviate the environmental impact of distribution.

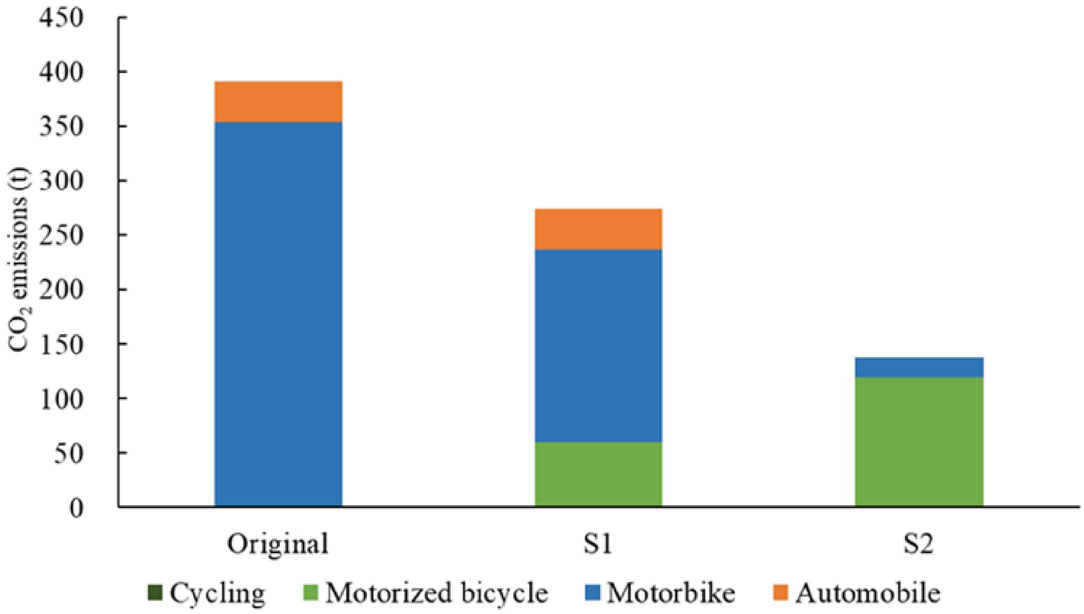

Figure 5.7 Differences in CO_2 emissions from OFD by changing the distribution method (Figure created by the author.)

5.5.3. Changing plastic containers

CO_2 emissions of PSP+PP, Bio-PE and PHBH using Japanese food were compared as an example. Due to data limitations, this analysis only considers the production of raw materials for plastic packaging containers and does not include the manufacturing process. Although Bio-PE is a bio-based plastic, it is not biodegradable, so incineration is considered as the suitable waste disposal option (Siracusa and Blanco 2020). On the other hand, PHBH is biodegradable, so it could be treated as plastic landfill waste when separated at source.

Figure 5.8 shows that PHBH material has the highest CO_2 emissions, followed by Bio-PE. We can find that new plastic production has much higher CO_2 emissions than PSP+PP. In the plastic production stage, CO_2 emissions from PHBH production were 1.35 times those of PS. Although PHBH is a biodegradable material, most plastic disposal in Japan is by incineration (Japan Waste Disposal Report 2023). The total CO_2 emissions of

PHBH are higher than conventional materials (PSP+PP). Therefore, from the perspective of CO_2 emissions, PHBH and Bio-PE materials are not environmentally friendly in Japan.

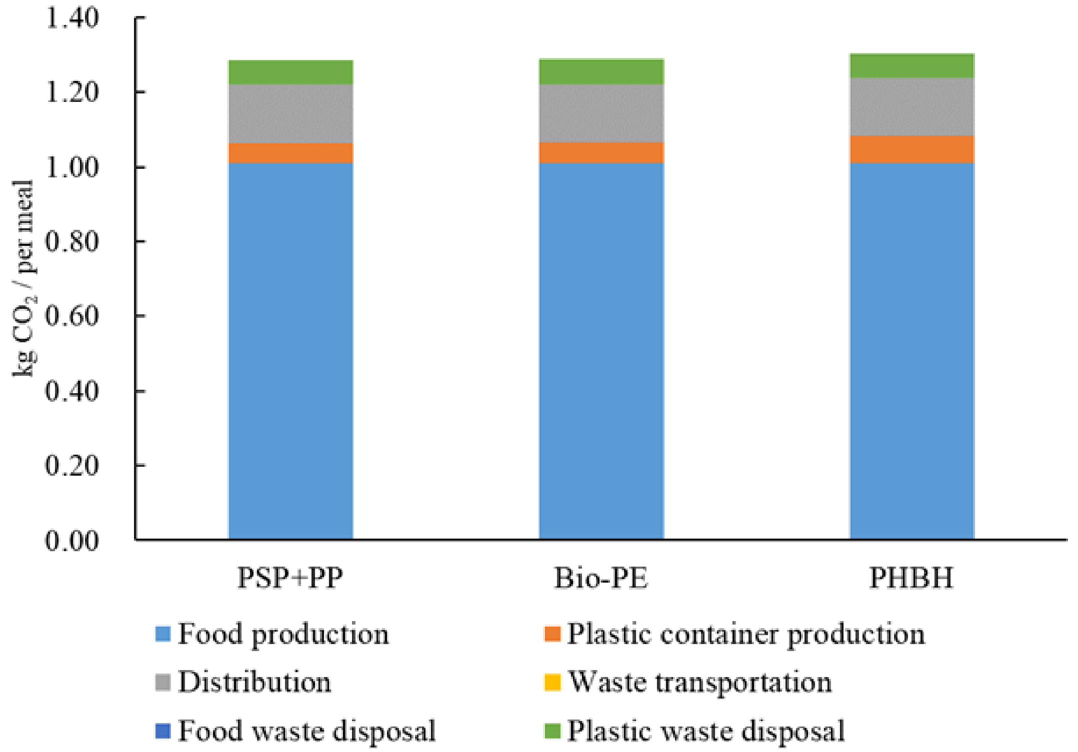

Figure 5.8 Differences in CO_2 emissions from OFD by changing the plastic containers. (Figure created by the author.)

5.6 Summary

This study evaluated the CO_2 emissions of an OFD order, considering multiple factors such as food options, types of plastic containers, delivery methods and distances, proportions of consumption, and methods of waste disposal. Scenario analysis can reveal how much each process contributes to overall CO_2 emissions, providing direction for reducing CO_2 emissions from OFD. It showed that food production was the largest contributor to CO_2 emissions. Choosing environmentally friendly food options can significantly reduce the total amount of CO_2 emissions that is generated by each OFD meal. On the other hand, when consumers leave leftovers, extra CO_2 emissions are generated during the production stage of the excess food, as well as during the collection, transportation, and disposal of food waste. Therefore, if restaurants could provide more options in terms of the volume of food, and if they could encourage customers to order appropriate amounts of food, it would make a major contribution to reducing CO_2 emissions.

On the other hand, the total amount of plastic required for each OFD meal is relatively small, and the delivery distance is also relatively short in Japan, resulting in a smaller environmental impact from the food portion. However, initiatives such as improving delivery methods and using "green" containers can contribute to reducing CO_2 emissions from OFD.

There is still much research to be done. Our next step will involve conducting interviews with OFD platforms, restaurant owners, and customers through surveys to gather real information and data. This will help us verify the results of our study and measure the actual amounts of food waste and plastic waste from OFD, allowing us to develop a more comprehensive environmental impact assessment of OFD.

6 Discussions: Low Carbon Resilience Governance Strategies and Institutional Recommendations

6.1 Disruptive events as a turning point for urban climate governance

In the fields of urban governance and disaster studies, the effects of crises are often measured by their immediate impact—such as death tolls, infrastructure damage, or economic losses. However, such impact-based evaluation tends to overlook a more fundamental question for urban low-carbon transitions: Which types of crisis-induced changes are more likely to be stabilized and institutionalized into new, lasting low-carbon regimes?

According to previous calculations, the impacts of earthquakes on cities are most evident in the energy, transport, and building sectors, all of which are closely linked to increased carbon emissions in the aftermath of such events (Figure 6.1).

In the energy sector, earthquakes often cause damage to infrastructure and lead to a temporary shift in the energy mix—away from low-carbon sources such as nuclear or renewables and toward fossil fuels, which are more immediately accessible. This shift results in low-efficiency power supply systems and a surge in carbon emissions. In response, many cities have begun promoting renewable energy sources, energy storage technologies, and distributed energy systems to improve energy resilience and sustainability. As a result of these efforts, the Feed-in Tariff policy (Ichigo Green Infrastructure Investment Corporation, 2012) has been introduced to encourage renewable electricity production, leading to a 20.84% reduction in carbon emissions from electricity supply. Additionally, the deployment of smart grid systems and energy storage (METI, 2015) has helped reduce indirect carbon emissions by approximately 20.54%, by balancing supply and demand more efficiently and reducing energy losses.

In the transport and building sectors, the core problem is also high carbon emissions, especially during post-disaster reconstruction. After earthquakes, increased movement of materials, use of machinery, and rapid rebuilding activities drive up emissions. To address this, policies have promoted the adoption of low-emission and fuel-efficient vehicles, supported by automotive environmental management plans (Bureau of Environment, 2018), which have contributed to an 8% reduction in vehicle-related carbon emissions.

Similarly, in the building sector, governments have responded by updating building regulations, emphasizing energy efficiency and sustainable construction standards. The key policies is the Zero Emission Building policy（Tokyo Metropolitan Government, Bureau of Environment, 2021); aimed at achieving long-term carbon neutrality goals. These initiatives not only reduce emissions but also enhance the city's preparedness for future disruptions by promoting more resilient infrastructure.

These policy shifts reflect how the challenges brought by earthquakes can serve as catalysts for sustainable transformation, accelerating progress toward low-carbon urban systems.

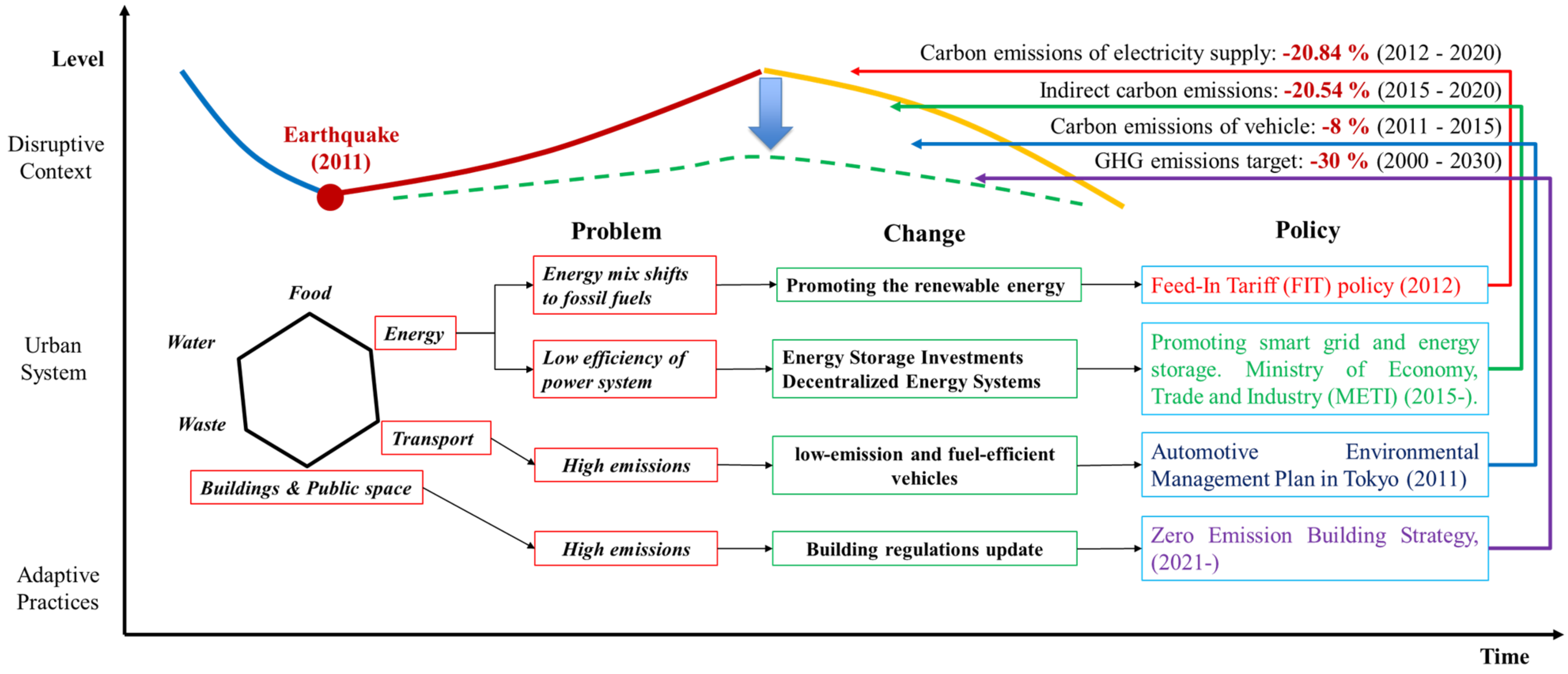

Figure 6.1 Institutionalization potential of earthquake-induced change
(Figure created by the author.)

The Figure 6.2 illustrates how the COVID-19 pandemic (2020) acted as a disruptive event, causing a temporary drop in carbon emissions, followed by a gradual rebound. The pandemic is positioned as a potential turning point in urban climate governance.

At the urban system level, COVID-19 influenced several sectors, with a particular focus on food, transport, and waste. The surge in OFD led to three major problems: over-ordering due to free delivery incentives, lack of carbon oversight in the distribution process, and increased food waste. These issues highlight the downstream behavioral impacts of the pandemic on urban carbon pathways.

In response to these issues, the Figure 6.2 presents possible adaptive changes. OFD platforms can offer more flexible food options to meet actual consumer needs and reduce waste. Additionally, optimizing delivery methods—such as through route planning or vehicle electrification—can help lower emissions from distribution.

The adaptive changes are linked to actual policy frameworks, particularly the Zero Emission Tokyo Strategy 2020. Three specific strategies are cited (Tokyo Metropolitan Government, Bureau of Environment, 2021): The Food Loss and Waste Reduction Plan, supporting better portion control and food waste reduction. The ZEV Promotion Strategy, encouraging cleaner delivery systems. And overall updates to the Zero Emission Tokyo plan, aligning urban responses with long-term decarbonization goals.

Finally, the Figure 6.2 quantifies the potential impact of these changes. With the proposed adaptations and policies in place, carbon emissions from the OFD industry could decrease by at least 16%, emissions from food distribution by nearly 29.96%, and emissions related to food waste by at least 25%. These numbers underscore the potential for behavioral and governance reforms to contribute significantly to urban emission reduction efforts.

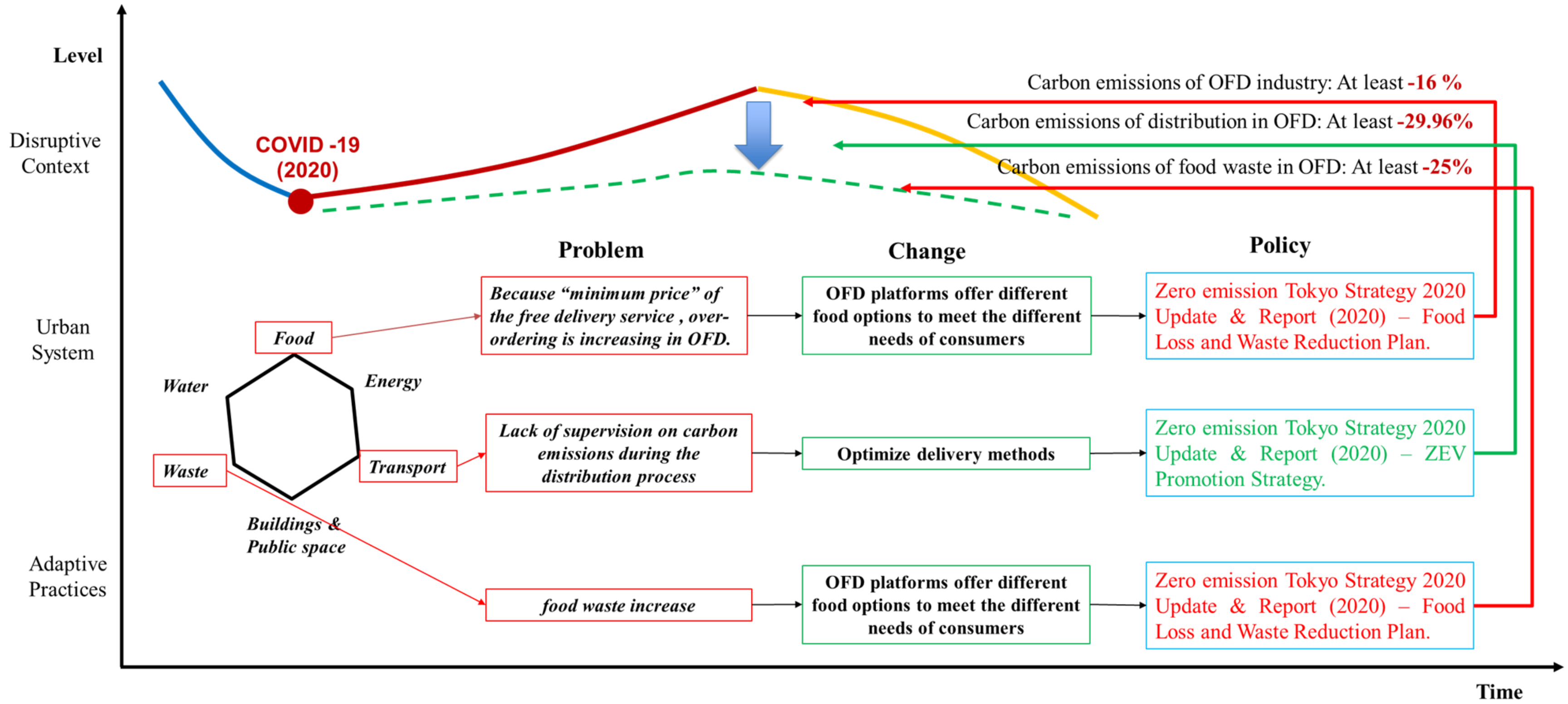

Figure 6.2 Institutionalization potential of pandemic-induced change

(Figure created by the author.)

6.2 Differences in mechanisms between earthquakes and epidemics

A central concern of this study is understanding the mechanisms through which different types of disruptive events affect the structural and institutional pathways of urban carbon emissions. By comparing two distinct events — the Great East Japan Earthquake (2011) and the COVID-19 pandemic (2020) — this study reveals how disruptions of different natures perturb carbon systems through different system layers and generate divergent responses in both infrastructure and behavior.

The earthquake represents a sudden, physical-institutional system shock, whereas COVID-19 exemplifies a persistent, social-behavioral disruption. Though both events triggered major societal responses, their respective mechanisms of influence on urban carbon dynamics are fundamentally different (Table 6.1).

(a) Type of Disruption

The earthquake caused sudden physical damage to energy infrastructure and urban lifelines, triggering immediate system-wide breakdowns. In contrast, the pandemic produced a prolonged disruption of daily practices and social systems, affecting mobility, consumption, and service provision over an extended period without destroying physical infrastructure.

(b) Affected System Level

While the earthquake primarily disrupted the urban system level — including centralized energy, housing, and transport—the pandemic operated largely at the practice level, altering how individuals interact with the city through work, travel, and consumption routines.

(c) Systemic Response

In the case of the earthquake, the collapse of Japan's nuclear-dependent centralized energy system led to:

A rebound to fossil fuels to compensate for supply shortages;

A policy shift toward distributed renewable energy systems in the medium to long term.

By contrast, COVID-19 led to the shutdown of in-person services, catalyzing the rapid rise of digital platforms, and accelerating the emergence of new consumption logics, such as OFD and remote work — changes that represent behavioral rather than infrastructural shifts.

(d) Carbon Emission Impacts

The earthquake induced a short-term increase in emissions due to reliance on fossil energy. However, it also opened up space for long-term emission reductions through energy diversification and distributed generation, driven by national energy reforms.

In contrast, COVID-19 led to an immediate decline in carbon emissions—due to reduced transportation and industrial activity — but the long-term impact remains uncertain, as it depends on whether newly adopted behavioral changes can be institutionally embedded and retained post-crisis.

This comparative analysis highlights that not all disruptions are equal in their influence on carbon systems. Physical system shocks and behavioral system disruptions trigger different transition pathways, with varying potentials for institutional stabilization. Understanding these mechanism differences is essential for crafting tailored governance strategies that transform crisis-driven change into long-term decarbonization.

Table 6.1 Summary of mechanism differences

Dimension of Comparison	**Earthquake**	**COVID-19**
Type of Disruption	Sudden physical damage to infrastructure	Prolonged disruption of social and behavioral systems
Affected System Level	Urban system	Practice
Systemic Response	Collapse of centralized energy; Rebound to fossil fuels; Shift to distributed energy policy	Shutdown of in-person services; Rise of digital platforms; Emergence of new consumption logics
Carbon Impact	Short-term rebound in emissions; Long-term reduction potential via energy reform	Short-term emission decline; Long-term potential depends on institutional integration

We divided the urban supply chain into three segments: upstream, midstream, and downstream (Figure 6.3). Upstream includes energy production, raw material extraction, and infrastructure-related sectors. Midstream involves processing, logistics, and service delivery, while downstream focuses on end-user behavior and consumption.

In this study, we found that earthquakes primarily disrupt upstream sectors, such as energy infrastructure and construction materials, due to physical damage and the need for large-scale reconstruction. These disruptions often result in increased carbon emissions from energy conversion and material production.

In contrast, epidemics like COVID-19 mainly affect midstream and downstream sectors, including transportation, retail, and consumer behavior. Lockdowns and mobility restrictions shift consumption patterns, reduce certain emissions temporarily, but also increase emissions in specific sectors such as OFD. These differences highlight the need for tailored decarbonization strategies according to the disruption type and its point of impact within the supply chain.

The 2011 Great East Japan Earthquake, the sharp increase in CO_2 emissions from the energy sector was due to the shutdown of nuclear power plants, which led to a shift to fossil fuel-based power generation. This made the energy sector's emission unusually high in this case. However, not all earthquakes lead to such energy system disruptions. In smaller earthquakes, power generation patterns might not change significantly. Still, most large-scale earthquakes — such as 2011 Great East Japan Earthquake or the 2016 Kumamoto Earthquake—cause serious physical damage, including broken buildings, and damaged roads, which trigger massive reconstruction efforts.

So, while the sectoral contribution to emissions may vary depending on the characteristics of the earthquake, the general pattern remains the same: upstream sectors such as energy, construction, and materials increase significantly. In this study, our goal is to provide an analytical framework. This framework can be applied to other cases— such as the Kumamoto Earthquake — by using available data to assess the carbon emissions in sectors such as buildings, transport.

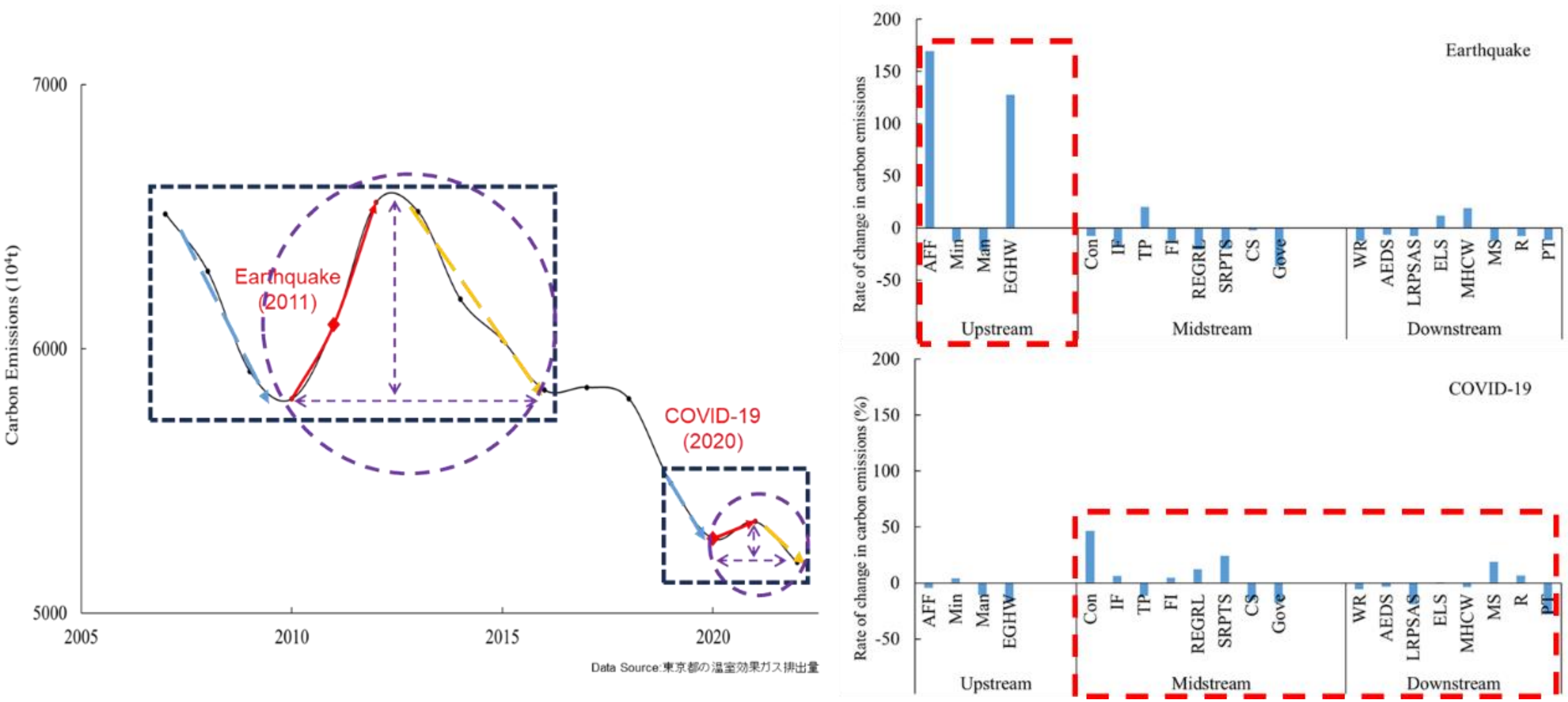

Figure 6.3 Impact of different disruptive events on carbon emissions in urban supply chains
(Figure created by the author.)

7 Conclusion

This study analyses the impacts of different types of disruptive events on the urban carbon emission system, using the earthquake and COVID-19 as two typical cases. It is found that ‘structural shocks’ such as natural disasters usually lead to changes in energy structure and infrastructure reconstruction in the short term, resulting in a sharp increase in carbon emissions, while ‘behavioral perturbations’ such as epidemics gradually change consumption patterns and lifestyles, indirectly affecting the structure of carbon emissions. Despite their different paths, both of them reveal the vulnerability and adjustment mechanism of the urban system after being hit by shocks.

However, this study further suggests that these shocks are not only risks, but also opportunities to reshape the urban system. Through policy interventions, institutional restructuring and behavioral guidance, it is possible to shift the path from an old pattern to a low-carbon transition towards a new pattern. For example, in post-earthquake infrastructure reconstruction, prioritizing the use of green building materials, distributed energy systems and energy-efficient design can transform the reconstruction process into a window of carbon reduction. Behavioral changes such as telecommuting, reduced commuting, and local consumption in the post-epidemic lifestyle reconstruction could also provide a long-term the study is based on a methodological approach.

Methodologically, this study integrates LCA and Environmentally EEIOA to develop a ‘Disruptive Context, Urban System, Adaptive Practices’ framework that can be used in urban policy design. This framework can be used not only to assess post-disaster emission dynamics, but also to pre-determine intervention scenarios that can assist urban policy makers in developing low carbon emergency response and resilience strategies prior to a disaster.

In summary, the trajectory of carbon emissions in cities is not always linear and stable, and the short-term impact of disruptive events as a perturbing variable should not be ignored, while the key lies in how to grasp the window of system restart after the event. Future research can further expand the types of events and city samples, and explore low-carbon recovery paths in different institutional and cultural contexts, in order to provide more adaptive policy tools and theoretical support for the carbon neutral process in global cities.

(a) Establishing a low-carbon orientated inter-departmental Plan B system for different types of Disruptive Events

In this study, we find that the impact of a disruptive event on urban carbon emissions does not only come from its destructive power, but also from whether the post-disaster response path is carbon-sensitive or not. In the case of the 2011 Great East Japan Earthquake, for example, Japan was forced to switch to large-scale thermal power generation in the wake of the devastating Fukushima nuclear power plant, which led to a sharp rise in carbon emissions in major cities such as Tokyo. This example shows that a Plan B arrangement without a low carbon perspective will increase the carbon emission of the disaster significantly.

Therefore, this study suggests that departments at all levels (energy, transport, waste management, building, etc.) should create specific departmental low-carbon plans for different types of disruptive events (e.g., short-term: earthquakes, typhoons; long-term: epidemics). This type of plan should not only preset the contingency plan, but also include the consideration of alternatives.

For example: Energy sector: In the event of a major thermal or nuclear power plant being destroyed, renewable energy reserves (e.g., mobile electric storage vehicles, solar panels, and large-capacity batteries), and behavioral controls to reduce electricity waste (e.g., energy-saving emergency orders) could be introduced in the short term; in the medium to long term, distributed energy systems should be incorporated into the design of the regional energy grid to increase resilience. Building sector: When planning temporary refuge facilities, give priority to modular buildings with solar energy and natural ventilation designs, and avoid the use of energy-consuming temporary building materials. Transport: In case of massive traffic disruptions, alternative public transport can be activated to reduce the carbon emissions caused by the temporary mass movement of private cars.

These Plan Bs are not only responses, but also alternative mechanisms that take carbon reduction as a core standard. Only by institutionalizing them into local and national energy and crisis management policies can cities avoid the reliance on high-carbon recovery paths after disasters and move towards a truly resilient and sustainable low-carbon transformation.

(b) Pre-disaster initiated public education and behavioral intervention mechanisms

If Plan B is considered as an institutional alternative pathway after a disaster, social education should be considered as a proactive intervention strategy initiated before the disaster. This study proposes to invest in public education and behavioral preconditioning mechanisms to mitigate possible future high-carbon responses before Disruptive Events even occur.

For example, in Japan, people have a high level of knowledge about the physical prevention of earthquakes, but little knowledge about the environmental aspects of response, such as how to rebuild in a low-carbon manner after a disaster, choosing energy-saving materials, and avoiding the use of single-use plastics. If the concept of carbon reduction after disaster can be conveyed through community seminars, disaster drills and school-based programmers, it will help to reduce the number of people who make decisions in a state of panic: Reduce the number of people making high-carbon decisions in a state of panic (e.g., hoarding highly-packaged products, buying large quantities of bottled water, etc.)

Raise public awareness of the relationship between behavior and carbon emissions, so that they will be more proactive in adopting environmentally friendly practices in the aftermath of a disaster; Promote collaborative governance within the community so that low carbon becomes the default consensus in the recovery process.

By injecting low-carbon concepts into social psychology and behavioral norms in advance, Disruptive Events is no longer just a technical or institutional challenge, but also an important node for public education and social resilience building.

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