Comparative Environmental Performance of E-commerce and Traditional Retail Channels

ADIL SHIAEB

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Faculty of Engineering

University of Ottawa

Contents

Abstract

Chapter One: *This study investigates the comparative environmental performance of e-commerce and traditional retail channels using a systematic literature review and content analysis approach. Given the pace at which e-commerce is penetrating global markets today, it is important to understand how this digital transformation is mitigating or contributing to the current climate crisis that is threatening the liveability of our planet. We find that, from a life-cycle perspective, e-commerce generally leads to better environmental outcomes than traditional retail. However, looking at individual logistical activities (production, warehousing, transportation, packaging) separately, e-commerce fares badly environmentally at the packaging stage, likely due to the vast number of small orders shipped individually and the use of corrugated cardboard boxes. In order to balance economic and environmental performance of e-commerce, this study shows developing environmentally-friendly packaging solutions is a key area to focus on.*

Chapter Two: *This study builds on Chapter One, which provided a comprehensive and up-to-date systematic review of the environmental impacts of e-commerce over traditional retail. The meta-analysis in this study estimates several successive regressions using data retrieved from the studies reviewed in Chapter One. Based on the regression results, we make two conclusions. First, on a Life-Cycle basis, switching from traditional retail to e-commerce does not seem to have any statistically significant impact on the environment. Secondly, we confirm the results of our systematic literature review that e-commerce packaging is an environmentally damaging activity. These two results taken together suggest that environmental benefits of other supply chain activities such as production, warehousing, transportation etc., offset damages from the packaging activity as the retail channel switches to e-commerce. In today's world where technological development occurs at a faster pace and a Coronavirus pandemic has reinvigorated the rate at which e-commerce is penetrating global markets, one takeaway from this study is that developing sustainable packaging solutions is a key area to focus on.*

Chapter Three: *This study utilizes the nonparametric EDM approach to investigate the impacts of increased e-commerce penetration on Canadian natural gas, motor gasoline and distillate fuel oil consumption. This approach overcomes the impracticality of specifying explicit equations for the analyzed economic data, given the potentially complex and chaotic nature of the underlying systems. We show that e-commerce did not influence Canadian residential, commercial, and industrial natural gas consumption over the 2016-2021 period. On the contrary, causality test confirmed causal forcing from e-commerce to Canadian motor gasoline and distillate fuel consumption for the 2019-2021 period. On average, Canadian motor gasoline and distillate fuel consumption decreased by 1.0% and 2.3% respectively for every additional percentage point increase in retail e-commerce sales. In addition, analysis using Australian data shows marginal effects for gasoline consumption, like Canada, are largely negative. However, unlike Canada where the impacts on diesel were negative, results for Australia and Taiwan show positive state-dependent effects of e-commerce on diesel use, a plausible outcome as the activity changes from passenger travel to freight transport with increased e-commerce penetration. Given the limited application of EDM in social sciences, and particularly in e-commerce research, this study augments the existing literature.*

Chapter Four: *This chapter integrates the analytical results from the first three chapters of the current study and provides targeted recommendations to consumers, firms, and governments. The analyses reveal two important conclusions: that e-commerce as a whole does not necessarily lead to negative environmental outcomes and that e-commerce packaging is environmentally damaging. Given these results, we recommend civil societies representing the public to educate consumers on environmental protection and climate change. For firms, in addition to prioritizing environmental and social responsibility, developing eco-friendly packaging solutions, and engaging in green marketing, we recommend them to invest in the development of sustainable e-commerce infrastructure to improve the long-term environmental performance of e-business platforms. For governments, the study recommends relevant state authorities to utilize the right policy levers to achieve better environmental outcomes, preferably through market-based solutions but also exploring other regulatory levers where market-based mechanisms are not suitable.*

Acknowledgments

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Finally, I would like to dedicate this work to my late parents without whom I would not be here today, and my family and friends for their dedicated support while completing my studies.

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Chapter One

A Comprehensive Review of the Environmental Impacts of E-commerce

1.1 Introduction

Since the mid-1990s e-commerce has rapidly grown and immensely revolutionized the way we do business. It has made buying and selling a lot more efficient by eliminating layers of intermediaries and hence bringing about substantial cost and price reductions along the supply chain. According to Statista Inc., worldwide Business-to-Consumer (B2C) sales stood at 3.59 trillion dollars in 2022 and are expected to grow at an annual rate of 12.24% over the 2022-2027 period[1]. Moreover, B2C user penetration, the percent of global population that had purchased products online, is approximately 54.1% in 2022 and is expected to reach 66.2 % by 2027 (Statista Inc., 2022).

E-commerce has been defined in several ways. According to the European Commission, e-commerce is "…any form of business interaction in which the parties interact electronically rather than by physical exchanges or direct physical contact" (EC, 1998). This is a broad definition that could include both Business-to-Business(B2B) and B2C interactions as well as sales of goods and services between private persons. Among the different definitions and characterizations of e-commerce, the Organization for Economic Co-operation and Development (OECD) definition is by far the most agreed upon, given the endorsement from member countries. It defines an e-commerce transaction as the "…sale or purchase of goods or services, conducted over computer networks by methods specifically designed for the purpose of receiving or placing orders." The OECD further expounds that it is the ordering method that needs to be online and not necessarily the payment and the ultimate product delivery.

[1] https://www.statista.com/outlook/243/100/ecommerce/worldwide#

According to Mangiaracina et al. (2015), several systemic factors, including the increased availability of broadband, the establishment of legal framework for consumer protection, and the development of information communication technology infrastructure, have contributed to the boom of e-commerce. And while e-commerce has revolutionized trade and increased wealth and socio-economic development, concerns about its environmental sustainability have recently emerged. The most affected are traditional retailers, which faced increased competition from e-commerce. Many traditional retailers tried to use both online and offline sales to survive or were forced to close store or accept reduced sales. E-commerce may also have negative consequences for public welfare as automation may lead to lost jobs, shifts in skilled labour, wealth redistribution and increase in wage gaps. Alternatively, one can also argue that e-commerce helps reduce prices and offer new products thereby increasing consumer surplus (Domadenik et al. 2018). The World Commission on Environment and Development defines sustainability as “development that meets the need of the present without compromising the ability of future generations to meet their needs”. The challenge of e-commerce, or any other business model for that matter, is to balance economic and environmental performance.

E-commerce, on one hand streamlines value-chains and eliminates intermediaries, thereby decreasing demand for energy materials. On the other hand, however, e-commerce reduces costs and prices along the supply chain, stimulating additional demand for products and services and hence leading to a greater use of energy materials. This increased energy consumption is primarily driven by higher production, additional packaging and increase in product distribution. Whether the positive value-chain-streamlining impact outweighs the negative price-induced rebound impact is unknown, and the conflicting evidence from the existing literature is a testament to this.

This systematic review attempts to provide a more universal understanding of the comparative environmental impacts of e-commerce and traditional retail channels and contribute to a meaningful debate on the issue. Specifically, the study addresses the following research questions: are the net life-cycle environmental impacts of e-commerce positive or negative? From a logistics perspective, how does e-commerce compare with conventional supply chains in terms of its impact on various environmental indicators? In the context of e-commerce and the environment, there are two reviews that have been published in the recent past: Mangiaracina et al. (2015) and Pålsson et al. (2017). This review differs from the above in two ways. First the above reviews only include articles published before 2015 and secondly, they are narrow in scope: Mangiaracina et al. (2015) focus on B2C e-commerce while Pålsson et al. (2017) only analyze the impact on energy consumption. As many articles have been published since 2015 in an era where more data is becoming available, and as there are environmental indicators beyond energy use, this study offers a broad up-to-date systematic literature review of e-commerce and environmental sustainability.

1.2 Literature Review

There are several channels through which e-commerce can negatively or positively impact the environment as compared to conventional trade. For instance, production changes from induced demand due to structural and behavioral changes of the consumer, different configurations in packaging, warehousing and transportation activities, and the manufacture, use and disposal of e-commerce-enabling technologies can lead to differences in energy consumption. Generally, transportation planning and management is the area most often tackled in the literature of e-commerce and environment sustainability (Mangiaracina et al. 2015).

First, e-commerce can negatively affect the environment directly through the manufacture, use and disposal of e-commerce-enabling information and communication technology (ICT) materials. ICT devices entail several components such as chips, batteries, and boards for which their manufacture can have direct effects on the environment. For instance, the manufacture of semiconductors leads to the emission of harmful gases, water and toxic wastes such as silicon (Berkhout & Hertin, 2004). Concerning the use of ICT devices, electricity use by office gadgets in the U.S. was estimated to range (8% to 13%), of the total electricity use, with a medium PC consuming roughly 1 kW/h in a normal working day (Berkhout & Hertin, 2004). Increased power supply may translate into increased fossil fuel consumption to generate the surplus electricity which can lead to increased greenhouse gases emitted by fuel combustion (EPA, 2018). In addition, the disposal of ICT devices has been argued to be a major source of environmental pollution. For example, in the U.S. ICT related wastes are not separated from normal waste products, and this non-separation leads to the same disposal mechanisms. Given that many ICT products contain several toxic materials that in normal cases would require to be treated prior to disposal, disposing them together with other normal waste, therefore, leads to a serious environmental hazard.

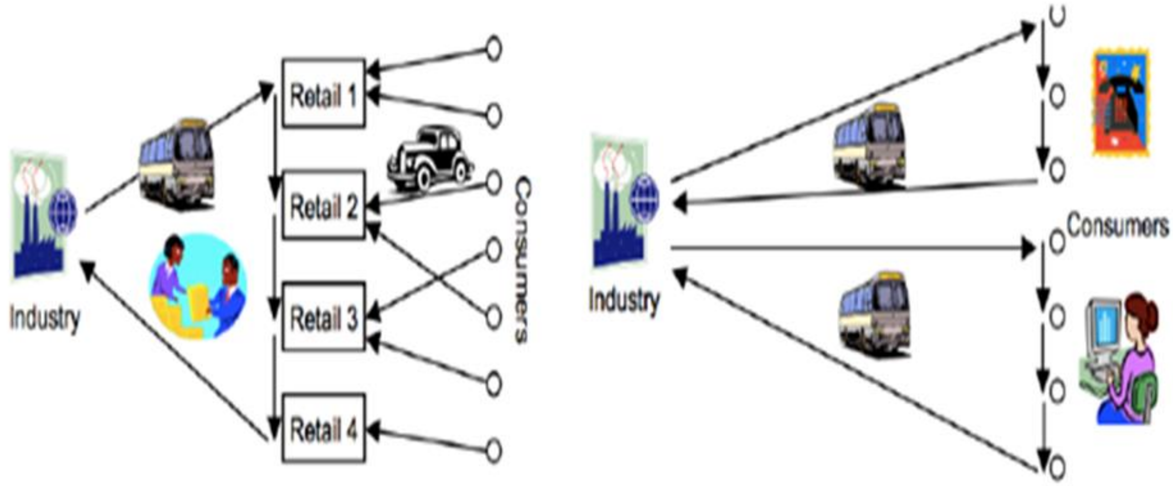
E-commerce can also negatively affect the environment through structural and behavioral changes in consumer behavior, through what is commonly known as the “rebound effect”. The rebound effect occurs due to reduction of prices and the subsequent increase in demand. This reduction in costs and prices along the supply chain stimulates additional demand for products and services and hence leads to a greater use of energy materials. This increased energy consumption is primarily driven by higher production, additional packaging, and an increase in product distribution.

Matthews et al. (2001), in their analysis of the different logistics networks for book retailing, found that assuming a return rate of 35%, e-commerce supply chain produces lower environmental impact in comparison to traditional bookstores. Williams & Tagami (2002) also study online book retailing and conclude that, while additional packing in e-commerce leads to more energy consumption per book than conventional bookstores, the relative efficiency of courier services in comparison to passenger cars in suburban and rural areas cancels out the negative impacts from additional packaging. Similarly, in studying the emission reduction potential of e-commerce by comparing a traditional bookshop with an internet bookshop, Borggren et al. (2011) show a net positive environmental impact from the internet bookshop due to fewer book returns and reduction of energy use at the traditional bookstore. Moreover, they indicate that customers can greatly reduce their environmental footprint by choosing to walk to the store or performing several activities within a trip that reduce the number of trips. Several other studies including Gay et al. (2005), Luo et al. (2001), Sivaraman et al. (2007), Xu et al. (2008) and Xu et al. (2009) suggest that energy and emissions savings are achieved through a shift to e-commerce from traditional stores.

On the other hand, some studies report negative or ambiguous life-cycle results. Fan et al. (2017), in their analysis of the environmental impacts of China's express delivery industry, find that production and distribution of express packaging materials alone can lead to greater environmental damage. Abukhader & Jönson (2003) conclude that "There is a general agreement that it is highly difficult, if not impossible, to state if the damaging effects of e-commerce on the environment can weigh over the advantageous effects or the contrary (p. 474)". Berkhout & Hertin (2004) argue that, in general, utilization of ICTs in business can lead to both negative and positive environmental impacts. It is, however, difficult to trace and measure these impacts as the relationship between ICTs and the environment is complex, uncertain, and scale-dependent (nonlinear and depends on the level of ICT deployment/e-commerce penetration). Cullinane (2009) concludes that it cannot be stated with any degree of certainty that e-businesses are more environmentally friendly than traditional stores. Finally, Fichter (2002) acknowledges that e-commerce is inherently neither environment-friendly nor environment-hostile. All these studies call for further research and more quantitative analysis in this field.

With respect to product distribution alone, as expected when conventional trade is replaced with e-commerce, the mode of transport changes from passenger transport to freight transport (Figure 1). As a result, differences in energy use and emissions result not only from changes in travel activity, but also from the emission intensity of the transport mode being used. For instance, heavy-duty trucks, marine and air transport used for package delivery are by far some of the most emission-intensive modes of transport. The existing body of studies cover a wide range of cases, from books to DVDs to grocery and find a wide range of e-commerce impacts on transportation energy use and emissions.

Figure 1: A comparison of transport demand between traditional stores and e-commerce



Source: Tseng et al. (2005)

Siikavirta et al. (2002) indicate that the passenger transport mode for store purchases is a major factor influencing the differences in energy consumption between e-commerce and conventional retail. In their study of electronic grocery (e-grocery) shopping, they found that "depending on the home delivery model used, it is possible to reduce the GHG emissions generated by grocery shopping by 18% to 87% compared with the situation in which household members go to the store themselves" (p. 93). Pålsson et al. (2017) conducted a literature review and content analysis in order to analyze factors determining the relative energy efficiency between e-business and traditional trade. Analyzing specific cases within eleven studies, they found that total energy consumption from transportation – and hence emissions – was larger in the traditional channel, as the reduction in energy consumption from passenger transport generally offset the increased energy use in freight transport under e-commerce. For instance, while e-commerce freight transport consumed more energy compared to traditional trade (with many cases showing about

10% more energy), the energy consumed by passenger transport in the traditional channel was significantly higher.

An earlier review, however, seems to come to a different conclusion. Mangiaracina et al. (2015) reviews the literature on the environment implications of B2C e-commerce from a logistics perspective. While they conclude that the existing literature generally does not indicate a consensus vis-à-vis the environmental impact of transportation activities related to B2C e-commerce, they nonetheless stress that some of the studies they reviewed show negative environmental impacts, mostly related to inefficient deliveries of packages. They make important observations about transportation-related emissions of e-commerce. First, the surge in e-business channels increased van traffic, a relatively more carbon-intensive mode of transport. Secondly, inefficient deliveries and returns handling can increase travel. Thirdly, shoppers tend to purchase from several online channels, each requiring a separate delivery, rather than from conventional stores where goods are purchased on a single trip. These factors highlight potential environmental damages that can arise from increasing uptake of e-commerce solutions. In any case, the environmental impacts of e-commerce arising from transportation activities surely depend on the mode of transport that replaces passenger travel. This is particularly demonstrated by Caudill et al. (2000) in their case study of desktop computers, which shows that if packages are shipped by air, online shopping can increase the environmental impact by up to 10%.

Along with warehousing and transportation activities, packaging is one of the key channels through which e-commerce can negatively impact the environment in comparison to conventional trade. Environmental damages relating to packaging can be attributed to the fact that the packaging system for products sold in conventional stores differs from those sold online. As an example, a book sold online may require an individual package while it can be sold without one at the regular bookstore. The environmental damage from packaging is even more pronounced when cardboard packaging is utilized.

The existing body of literature covers a wide range of cases, from books to DVDs and provides several indicators that can be used to illustrate the impacts of e-commerce on the environment. These indicators include air pollutants, greenhouse gas emissions, as well as a measure of the amount of waste generated by e-commerce relative to conventional trade channels. In their review of 56 papers published between 2001 and 2014, Mangiaracina et al. (2015) find that about 20% of the reviewed papers address the 'packaging' theme, which speaks to the importance of packaging in e-commerce from a sustainability perspective. Their findings also indicate that, from a product-packaging standpoint, e-commerce is generally thought to affect the environment negatively due to the individual packaging required to ship a few products to the customer.

However, when physical products such as music disks are replaced by online downloads, the impact of e-commerce on the environment largely becomes positive, as no packaging is required – an exception being multiple streaming of the same content which may lead to more environmental damages (Nair et al. 2019). In addition, the emergence of data centers, software networks and artificial intelligence (AI) consume a substantial amount of energy in their operations, while requiring devices that pollute the environment in production and disposal. E-waste management and disposal is often ignored by municipalities since e-waste recycling and treatment facilities require high capital investments and few countries allocate budgets to E-waste management (Rautela et al. 2021).

Focusing on energy use, Pålsson et al. (2017) conducted a structured literature review and a content analysis to determine factors affecting the relative energy efficiency of e-business and traditional trade. Analyzing specific cases within the studies, they find that the additional packaging required under e-commerce channels led to significantly higher energy consumption and hence possibly larger environmental damage. What is surprising is that, in most cases, the energy use from packaging more than quadruples as a result of switching from conventional trade to e-commerce. These results have important implications for environmental sustainability given the pace e-commerce is penetrating global markets today[2].

Several other peer-reviewed studies came to similar conclusions. Van Loon et al. (2015), in their analysis of greenhouse gas emissions from online retailing of fast-moving consumer goods, argue that e-commerce can be made more environmentally friendly by encouraging consumers to maximize the basket size as well as utilizing less energy-intensive packaging systems. According to the study, "100 g of corrugated cardboard plus limited amounts (33 g in total) of filling material, results in 181 g CO_2-eq per item" (p. 484) compared to shopping bags in conventional trade that result in about 11 g CO_2-eq. As a result, the environmental impact of shopping bags used in traditional stores is far lower due to the limited amount of packaging used. Borggren et al. (2011), in their study comparing the environmental impacts of a traditional bookshop versus an internet bookshop, find that e-commerce can contribute to negative environmental outcomes due to the individual packaging required to ship a few products to the customer. Fichter (2002) argued that one of the key sustainability concerns about e-commerce is the added product packaging that is needed for product fulfillment and delivery.

Product packaging seems to be one principal area where the existing body of literature unanimously points to increased energy use and environmental damages as a result of shifting from

[2] According to Statista Inc. (2022), Business-to-Consumer user perpetration, the percent of global population that had purchased products online, was about 54.1 % in 2022 and is expected to reach 66.2 % by 2027.

traditional channels to e-commerce. As the packaging used in e-commerce channels tends to be corrugated cardboard boxes, it has implications for environmental sustainability, both in terms of the energy required to produce the cardboards and the additional energy use related to inefficient loads during transportation. Nonetheless, there can be limitations in these studies in assessing the channels through which e-commerce can negatively or positively impact the environment. Oversimplifications in modelling approaches and assumptions, including the products and the delivery channels assessed can bias the results. Certainly, many of the studies acknowledge that the interaction of e-commerce and the environment is complex and scale-dependent, which makes the net environmental impacts very difficult to measure. There is thus a need for more complex and large-scale quantitative research in this area.

1.3 Methodology

This systematic review uses a three-step approach: material collection, material selection, and evaluation of selected studies. In the material collection, a search strategy was developed, and a unit of analysis defined. For the purpose of this review, the unit of analysis is a single study that investigates the impact of e-commerce on the environment. Relevant papers were identified through carefully selected keywords that were combined to formulate an inclusive search strategy (Table 1). In order to minimize reviewer bias, the keywords and the search protocol were reviewed by scholars at the Ottawa-Carleton Graduate School of Economics. Furthermore, to ensure the material collected is inclusive, additional articles were identified through reviewing the references of relevant articles from the database search.

During the material collection, three library databases were searched: the Web of Science, Econlit and Google scholar. The Web of Science database includes 1700 scholarly social science journals as well as material from thousands of science and technology journals. Econlit is a comprehensive database of the world's economic literature covering over 750 major economics journals, while the Google Scholar index includes most peer reviewed online academic journals and is estimated to contain over 160 million records (Orduña-Malea et al, 2015).

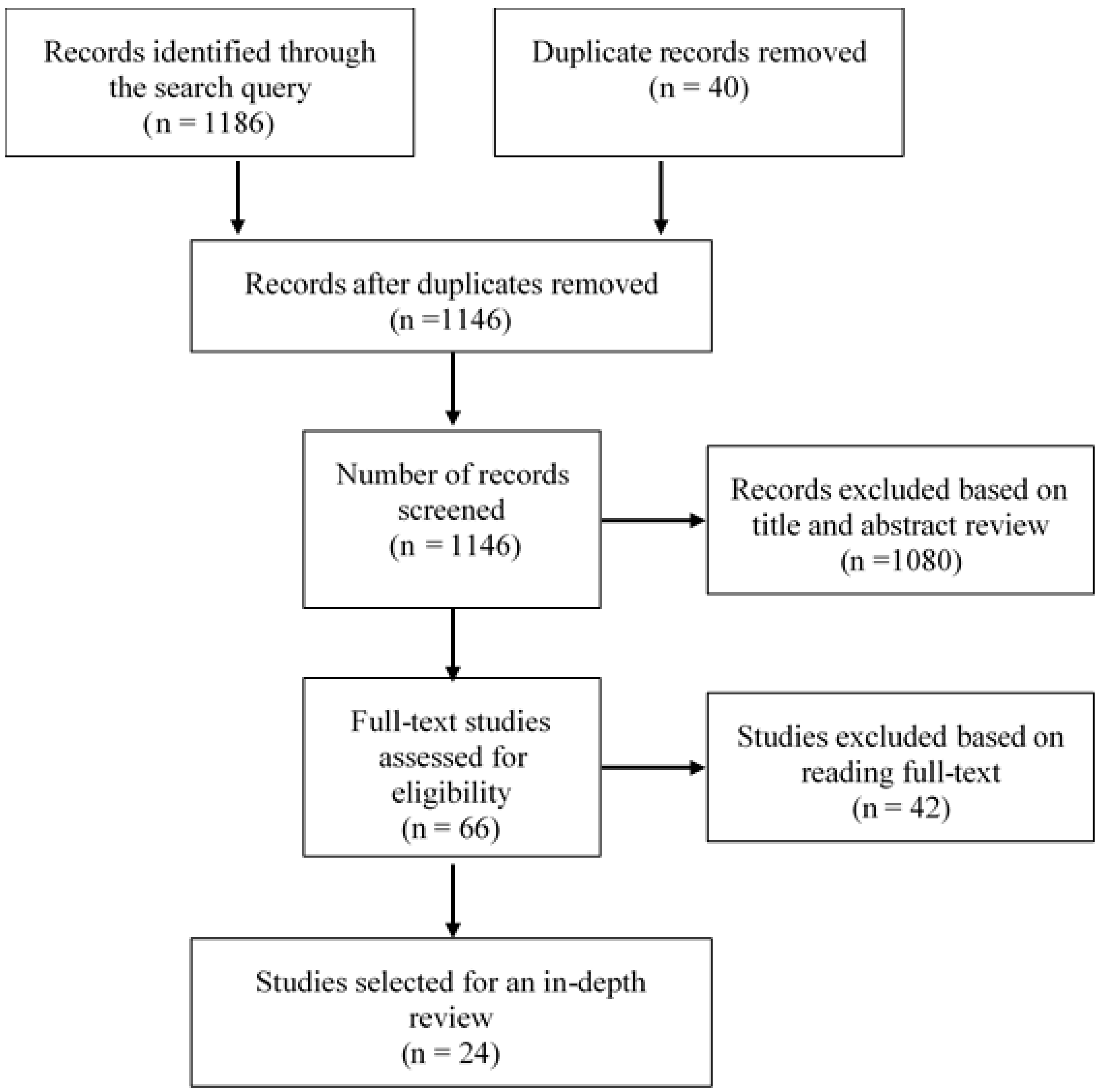
Table 1: Search query keywords

Keyword(s) 1	Keyword(s) 2
'E-commerce' or	AND
'Online shopping' or	'Emissions' or
'E-business'	'Environmental impact' or
	'Energy use' or
	'Environmental performance' or 'Environmental sustainability' or
	'pollution'

In the material selection, a selection criteria was developed: A study would be selected if it clearly addressed the impact of e-commerce or e-commerce solutions on the environment and was written in English. As e-business is a fairly new phenomenon, publication years were limited to the last two decades (1997-2018) - a period that adequately covers the advent and expansion of e-commerce technology. In addition, based on a cursory scanning of the titles and abstracts, articles outside the scope of this study were excluded. Afterwards, the remaining studies were carefully reviewed to see if they clearly address the research questions and/or if they contain enough details about the research methods. For example, did the study clearly address the environmental impacts of e-commerce; is the research methodology clear and logical; is the study design appropriate for the research question; does the study add new insights and data or it is just a plain review of existing literature? This process was used to retrieve relevant studies that were earmarked for an in-depth review.

Out of the 1186 records found, 40 were eliminated due to duplication. Title and abstract reviews eliminated a further 1080 records as these records did not explicitly address the research questions. The remaining 66 studies were carefully evaluated, to see if they clearly addressed the research questions and contained numerical details about the impact of e-commerce on the environment. This last step resulted in 24 papers, published between 2000 and 2020, which were selected for an in-depth review. Figure 2 provides an overview of the material selection process.

Figure 2: Studies selection flow chart



In the evaluation of the full-text studies, a thorough review was conducted to retrieve data related to the characteristics of the studies as well as environmental sustainability indicators. Information such as author's name, year of publication, study title, journal and country information were automatically generated from the search results, while the research methods and results data were manually collected in an spreadsheet while reading the selected studies. A descriptive statistical analysis was performed on the data gathered from the chosen articles.

1.4 Results and Discussion

The 66 full-text studies assessed for eligibility all addressed the topic of environmental sustainability and e-commerce (Appendix 1), but only 24 conducted comparative case studies with numerical results. The full-text studies were published between 2000 and 2020, with a growing trend from 2000 to 2002, followed by sporadic publications in the next few years and a large number in the late 2000s (Appendix 2). From early 2010s, an upward trend emerges, culminating with a peak of 8 publications in 2020. As Mangiaracina et al. (2015) point out, these trends are explained by two factors. The first is the interest in e-commerce by the business community which grew until the bubble burst in 2000, became stable for a few years and then rose again. It seems that researchers have responded to these issues given the time it takes to carry out research and prepare a paper for publication. Many of the earlier studies acknowledge the difficulty in tracing and measuring the net environmental impacts of e-commerce and suggested for more quantitative research in this area. The second factor which explains the upward trend from early 2010s is related to the increasing environmental consciousness in recent years as e-commerce became a mainstream business model. These later studies started warning very clearly about the environmental impacts of e-commerce packaging, transportation, and data centers, especially when non-renewable energy resources are used.

The studies were published in 49 scientific journals, with a mean publication value of 1.4 per journal (Appendix 3). The *Journal of Industrial Ecology* represented the largest number of publications with seven papers, followed by the *Journal of Transport and Environment* at four and the *Journal of Cleaner Production* and the *IEEE International Symposium on Electronics* and the Environment, each with three publications. The remaining journals had one or two publications each. Looking at the countries where the studies were published, the largest share (22.7%) of the reviewed publications came from a United States first author (Appendix 4). The United Kingdom followed with 13.6% of the publications, while Sweden, China and Germany had 10.6%, 9.1% and 7.6% respectively. As Mangiaracina et al. (2015) point out, these countries represent the main e-commerce markets and hence it is not surprising to see their research community paying more attention to the sustainability impacts of e-commerce solutions.

Out of the 66 full-text studies, only 24 conducted comparative case studies and provided numerical results. A total of 97 data records were collected from the papers, with each record providing environmental impacts data for both retail channels, either on a life-cycle basis or individually for each of the different logistical activities, and for the various environmental indicators (Appendix 5). About half of the records (46.4%) were impacts based on life-cycle assessment (Table 2). Looking at individual logistical activities (production, warehousing, transportation, packaging), transportation-related environmental damages were predominantly addressed (30.9%). This is not surprising as transportation planning and management is the area most often tackled in the literature of e-commerce and environment sustainability (Mangiaracina et al. 2015).

Table 2: Distribution of logistical activities in data retrieved from the studies

Logistical Activity	Count
Life-Cycle	45
Transportation	30
Packaging	13
Production	8
Warehousing	1

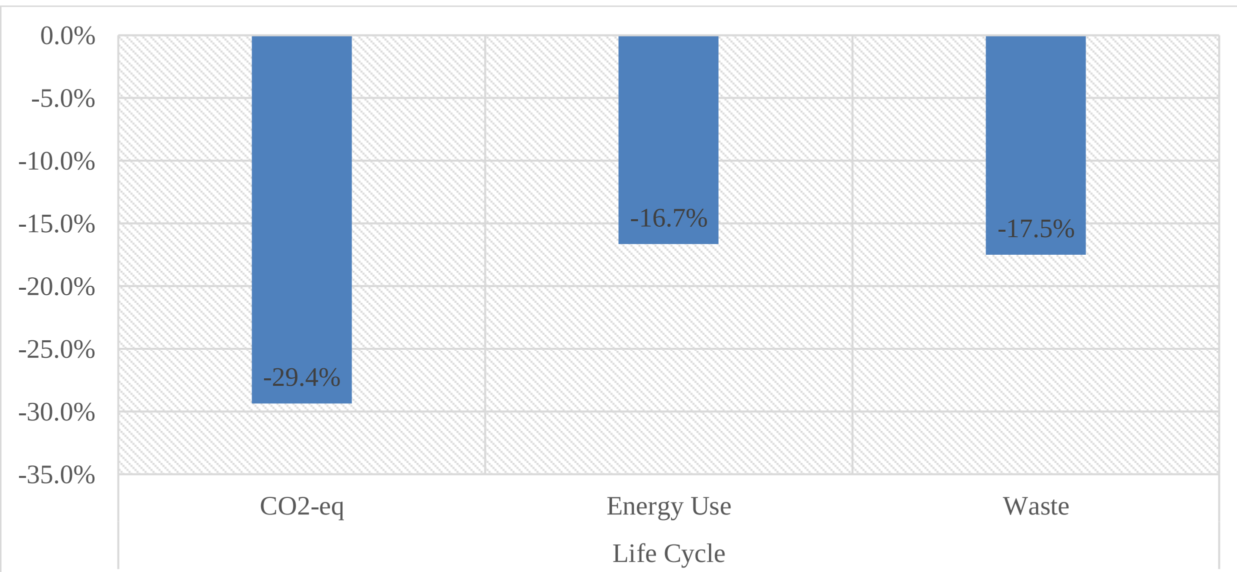
In terms of environmental indicators addressed, records on impacts of the two retail channels on energy use dominate (45.4%), followed by impacts on CO_2-eq emissions (28.9%) and hazardous waste (10.3%). A limited number of records address the consequences of retail choice on other pollutants (Table 3). In addition, a couple of studies reported Nitrous Oxide emissions in addition to CO_2-eq, while one study reported Methane emissions. The analysis in this section will focus on the energy use, CO_2-eq emissions and hazardous waste indicators, given the lack of adequate data for others.

Table 3: Distribution of environmental indicators in data retrieved from the studies

Environmental Indicator	Count
Energy use	44
CO_2-eq	28
Waste	10
SO_2-eq	4
CO	4
Other	3
N_2O	3
CH_4	1

As expected, the data collected from the 24 published studies report impacts in a variety of units, including mass units (kilograms, tones etc.), energy units (Joules), length units (kilometers) and in percentages. To normalize this data for analysis, we converted all the impacts reported to dimensionless percentages, using the reported values for the traditional channel as the baseline. Based on simple averages of the percentage environmental impacts, we find that, at the life-cycle level, e-commerce generally tends to have positive impacts on the environment (Figure 3). The average impact of e-commerce over the traditional channel for the energy use indicator is -16.7%, more or less similar to the results found by Pålsson et al. (2017) review who only investigated the impact of e-commerce on energy consumption. The average differences for the CO_2-eq emissions and hazardous waste indicators are -29.4% and -17.5% respectively. Impacts on related indicators such as energy consumption and CO_2-eq emissions may not be aligned as they may not be reported together by every study.

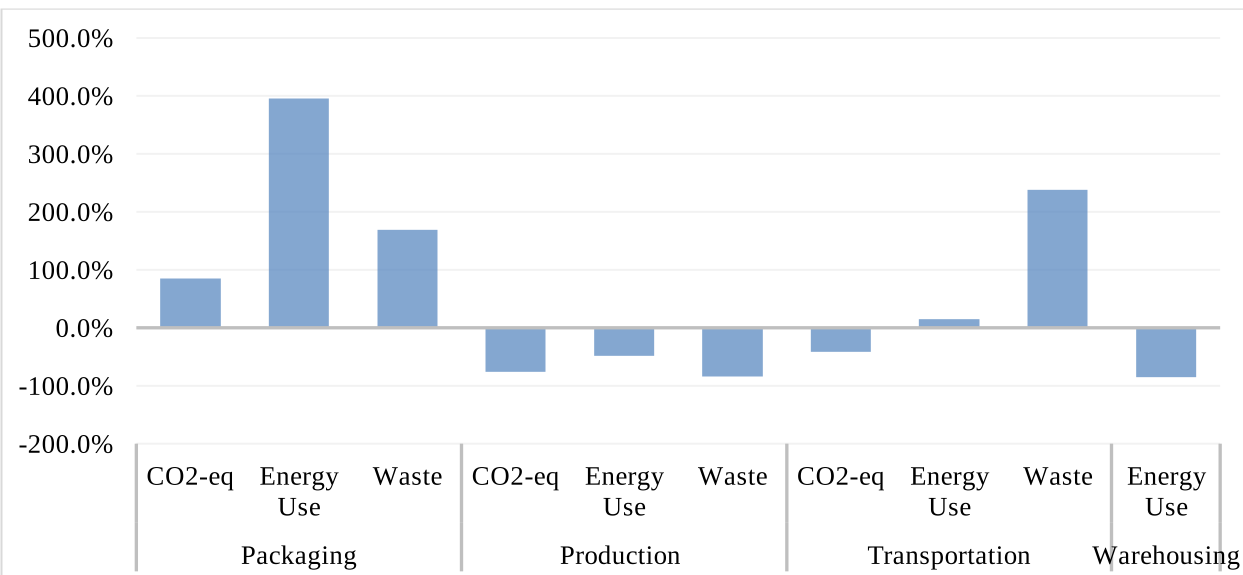
Figure 3: Simple averages of the life-cycle environmental impacts of e-commerce over traditional retail



Looking at individual logistical activities separately, the packaging phase of the supply chain seems to be the only area where e-commerce negatively affects the environment. As shown in Figure 4, the energy consumption, CO_2-eq emissions and hazardous waste output are considerably higher in the e-commerce system than in the traditional brick and mortar retail system. The reason for this is that packaging requirements are greater in the e-commerce system, given the vast number of small orders that need to be individually shipped. In addition, packaging used in e-commerce channels tends to be corrugated cardboard boxes which has implications for environmental sustainability in terms of the energy required to produce them.

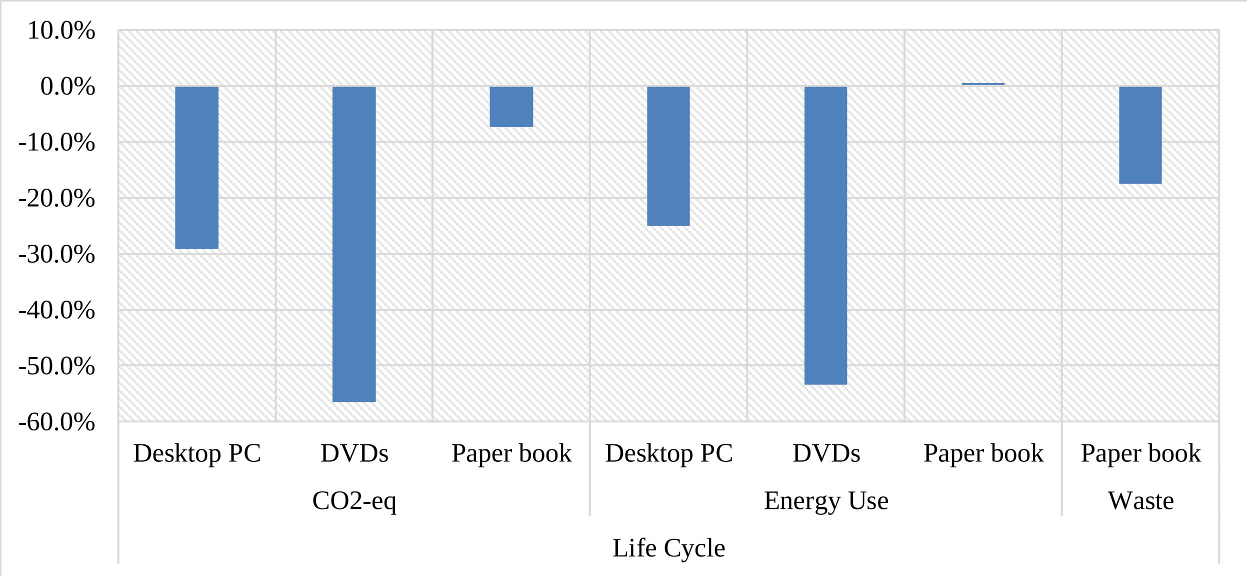
The other phases of the supply chain (production, transportation, and warehousing) generally seem to consume less energy and produce less CO_2-eq emissions and hazardous waste under the e-commerce system. The small positive increase in transportation energy use is due to an outlier record from one study where the authors assumed e-commerce deliveries will replace walking or biking in a densely populated urban area, hence resulting in substantially higher energy consumption under the e-commerce option. Furthermore, the positive increase in transportation waste in Figure 4 comes from a couple of studies by the same authors and is therefore not a statistic based on an adequate number of data points.

Figure 4: Simple averages of the environmental impacts of e-commerce over traditional retail for individual logistical activities



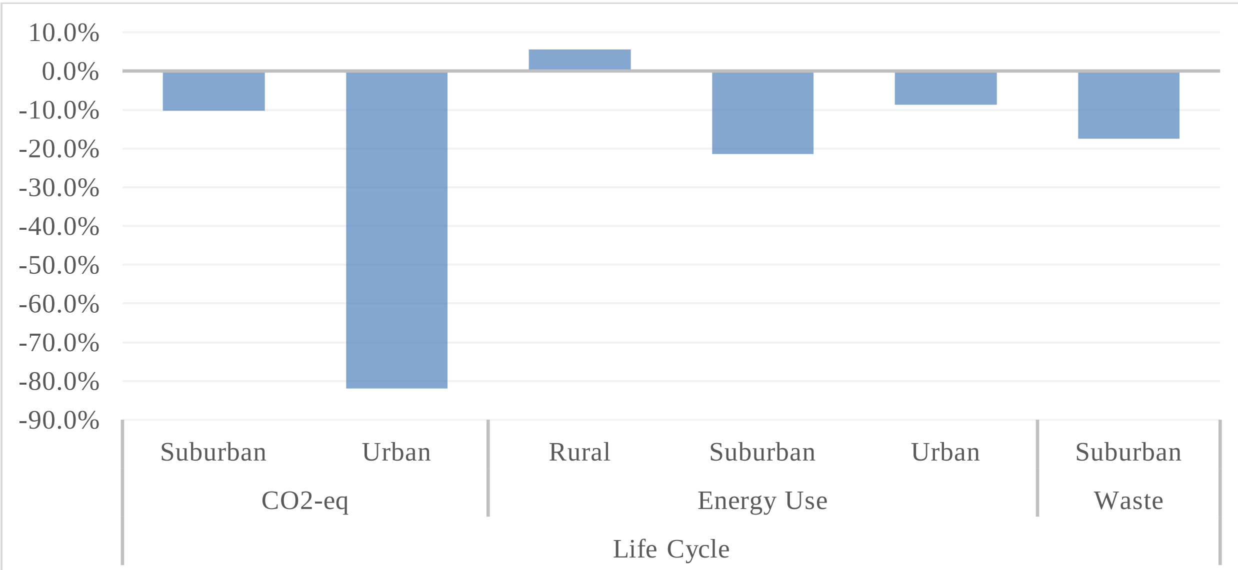
When it comes to the type of product studied, paper books form the majority, representing 53.6% of total records, followed by personal desktop computers at 13.4% and DVDs at 12.4% (Appendix 6). Other products including grocery, telework, parcel, flash drive, among others, each accounted for under five percent of total records. Analyzing the data where the product type is fixed can provide further insights and more refined results, and as Figure 5 shows, energy consumption, CO_2-eq emissions and hazardous waste production are lower in the e-commerce system than in the traditional channel based on a life-cycle assessment. Again, the small positive increase in energy use in the paper book category is due to the effect of one study which reports substantially higher energy consumption under the e-commerce option, particularly for the packaging phase and to some extent, transportation. Although some of the studies providing this data are dated given the recent digitization of books and the launch of streaming services for films, these results underscore the environmental benefits that could be achieved with other fast moving consumer goods under the e-commerce channel.

Figure 5: Simple averages of the environmental impacts of e-commerce over traditional retail by product type



In addition to product type, the environmental performance of e-commerce will likely depend on population density of the area studied. E-commerce can result in more energy efficiency in densely populated areas due to consolidated and efficient trucking systems (Williams & Tagami, 2002) but also in sparse areas, as courier services that replace personal shopping trips could save energy (Matthews et al., 2001). While some of the studies in this review do not explicitly identify the type of population area, we did our best to identify and categorize population densities based on the cities referenced in the case studies. Records involving suburban areas accounted for 59.8% of the data collected, followed by urban areas at 25.8% and rural at 4.1% (Appendix 7). We could not identify population density for 10.3% of the records. Regarding the impact of population density on the environmental performance of e-commerce, this study did not find any pattern between urban versus suburban area (Figure 6). The result for rural areas comes from a couple of studies and is therefore not a statistic based on an adequate number of data points.

Figure 6: Simple averages of the environmental impacts of e-commerce over traditional retail by population density



Based on data collected from the existing body of literature, e-commerce appears to provide positive impacts on the environment from a life-cycle perspective. Looking at individual logistical activities separately, the packaging phase of the supply chain seems to be the only area where e-commerce negatively affects the environment. While these results are intriguing and generally point to positive environmental outcomes of e-commerce (except for packaging), they come with several caveats.

First the data is collected from different papers published over a span of two decades, with different methodological approaches, assumptions, and geographical scope, which makes comparing results across the papers difficult. Secondly, as the interface between e-commerce and the environment can be quite complex and scale-dependent, oversimplifications of real-world situations in the reviewed studies could mean inherently inaccurate measurement of impacts.

Thirdly, the analytical results of this study are based on normalized simple averages of the data collected from the reviewed papers, and given the differences in methodology, assumptions and scope discussed above, the magnitudes shown may not reflect a good estimate of the environmental impacts of e-commerce.

However, the distribution and overall direction of the impacts reveal important insights vis-à-vis e-commerce systems and environmental sustainability. First, energy consumption, CO_2-eq emissions and hazardous waste production in the packaging stage are shown to be higher in the e-commerce system than in the traditional system, and this is likely due to the vast number of small orders that need to be individually shipped as well as the use of corrugated cardboard boxes for packaging. Secondly, from a life-cycle analysis perspective, the aforementioned environmental indicators are lower in the e-commerce system, suggesting the benefits from other stages of the supply chain (production, transportation, and warehousing) outweigh the damages from packaging. For firms and policy makers to balance economic and environmental performance of e-commerce, this study shows developing environmentally-friendly packaging solutions is a key area to focus on.

1.5 Conclusion

This chapter investigates the comparative environmental performance of e-commerce and traditional retail channels. Since the mid-1990s, e-commerce has rapidly grown and immensely revolutionized the business world. Giant multinationals like E-bay, Amazon and Alibaba have emerged and replaced traditional stores. From an environmental sustainability perspective, this digital transformation, on one hand streamlined value-chains and decreased demand for energy materials. On the other hand, however, it reduced costs and prices along the supply chain, stimulating additional demand for products and services and thus leading to a greater use of energy materials. With greater use of energy materials, comes greater environmental degradation, although the degradation level will depend on the type of energy used.

The global policy leaders of today are desperately trying to deal with a major climate crisis which threatens the liveability of our planet. Given how factors such as the increased availability of broadband internet and the development of ICT infrastructure are contributing to the pace at which e-commerce is penetrating global markets today, it is important to understand how this digital transformation of the business world is working against or contributing to the climate change mitigation efforts.

This study attempts to provide a more universal understanding of the net environmental impacts of e-commerce and further a meaningful debate on the issue. Specifically, it addresses the following research questions: are the net life-cycle environmental impacts of e-commerce positive or negative? From a logistics perspective, how does e-commerce compare with conventional supply chains in terms of its impact on various environmental indicators? The bulk of the current literature on e-commerce and the environment utilizes microeconomic, case-specific analyses to assess the impact of e-commerce on the environment.

Based on data collected from the reviewed papers, e-commerce appears to provide positive impacts on the environment from a life-cycle perspective. Looking at individual logistical activities separately, the packaging stage seems to be the only area where e-commerce negatively affects the environment, and this is likely due to the vast number of small orders that need to be individually shipped as well as the use of corrugated cardboard boxes for packaging. As a result, developing environmentally-friendly packaging solutions is a key area for businesses and policy makers to focus on.

Chapter Two

A Meta-analysis of Studies on E-commerce and Environmental Sustainability.

2.1 Introduction

In Chapter One, we conducted a systematic review that provided a general understanding of the net environmental impacts of e-commerce. In the context of e-commerce and the environment, the systematic review in the first chapter differed from earlier reviews such as Mangiaracina et al. (2015) and Pålsson et al. (2017) in two ways. First the earlier reviews only included articles published before 2015 and secondly, they are narrow in scope: Mangiaracina et al. (2015) focus on B2C e-commerce while Pålsson et al. (2017) only analyze the impact on energy consumption. As many articles have been published since 2015 in an era where more data is becoming available, and as there are environmental indicators beyond energy use, Chapter One offered a broad up-to-date systematic literature review of e-commerce and environmental sustainability.

Based on simple averages of the percentage environmental impacts of e-commerce over traditional retail, we found that e-commerce generally tends to have positive impacts on the environment, except for the packaging phase. However, these results come with a limitation as the analytical results are based on normalized simple averages of data collected from different papers published over a span of two decades. Given the differences in research methodologies, study assumptions and scope, the direction and magnitudes calculated may not be reflective of the impact of e-commerce on the environment.

Chapter Two therefore attempts to address this limitation. It examines how the reported relationship between indicators of environmental performance (i.e., Greenhouse Gas emissions, energy use intensity, Criteria Air Pollutants and waste generated) and the choice of trading channel (e-commerce versus traditional) is influenced by different characteristics of the studies reviewed in Chapter One. Specifically, we conduct a meta-analysis that attempts to understand the degree to which differences in the studies may be contributing to the direction and magnitudes of the estimated impacts. To do so, we estimate several successive regressions analyses that control for the different study characteristics; for example, differences in the type of product studied, study region, population density, type of logistical activity assessed and the year of study. A total of 97 data records that were retrieved from the reviewed studies form the basis of this analysis.

Based on the regression analysis, we confirm a key result of the systematic literature review. After controlling for the different study characteristics, the reputation of e-commerce packaging as an activity that negatively affects the environment continues to stand out. The regression results show that, relative to a life-cycle activity[3], the e-commerce packaging activity produces a worse-off outcome for the environment as the retail channel switches from traditional to e-commerce. Even with various forms of the dependent variable (the impact of e-commerce over traditional retail), alternative regression models as well as a Box-Cox transformation of the dependent variable to achieve normal and homoscedastic error terms, the significance of e-commerce packaging as an environmentally damaging activity continues to stand out.

The reason e-commerce fares badly environmentally at the packaging stage over the traditional retail channel is likely related to the fact that packaging requirements are greater in the e-commerce system, given the vast number of small orders that need to be individually shipped. In addition, packaging used in e-commerce channels tends to be corrugated cardboard boxes, which has implications for environmental sustainability in terms of the energy required to produce them.

[3] The Life-Cycle activity encompasses all the activities along the supply chain, from sourcing raw materials to the consumption of the final product.

2.2 Methodology

This meta-analysis attempts to understand the degree to which differences in the studies may be contributing to the direction and magnitudes of the estimated impacts. To do so, we estimate several successive regressions analyses that control for the different study characteristics; for example, differences in the type of product studied, study region, population density, type of logistical activity assessed and the year of study.

The primary regression equation estimated is as follows:

$$Y_i = \alpha + \sum_{i=2}^{k} \beta_i X_i + e_i; \qquad (1)$$

where Y_i is the estimated environmental impact of e-commerce over traditional retail, gathered from the studies; X_i represents characteristics of the studies (region, population density, type of product, etc.) that may be contributing to the direction and size of the estimated impacts and e_i is an idiosyncratic error term. In order to check whether a relationship does in fact exist, the 95% confidence intervals were produced, with non-zero intervals indicating a relationship that is statistically significant.

As mentioned earlier, successive versions of equation (1) were estimated. The first regression equation [(2) below] uses the percentage performance of e-commerce over traditional channels for the various environmental indicators as the dependent variable:

$$\text{RelativeImpact}_i = \alpha + \beta 1\ \text{LogisticalActivity}_i + \beta 2\ \text{EnvironmentalIndicator}_i + \beta 3\ \text{ProductType}_i + \beta 4\ \text{PopulationDensity}_i + \beta 5\ \text{StudyRegion}_i + \beta 6\ \text{Year}_i + \varepsilon_i \qquad (2)$$

Note that the regressors are all categorial variables where logistical activity = {life-cycle, transportation, packaging, others (production, warehousing)}, environmental indicator = {carbon dioxide equivalent (CO_2-eq), energy use, waste, others}, product type = {paper book, desktop personal computer (PC), DVDs, others), population density = {urban, suburban, rural, unknown}, study region = {Asia, Europe, North America}, and year = {2000,….,2020}. This means that the coefficients of the categorical independent variables estimate the effects of a category relative to a reference case, with the reference case being automatically selected by the R software used to conduct the analysis. We have included most of the possible explanatory variables from the studies that could affect the relative impact of ecommerce over traditional retail, thus minimizing omitted variable bias.

Given that the data used for the analysis comes from a systematic survey of experiments from different journal articles published over several decades, the likelihood of running into heteroscedasticity and non-normality problems is high. As the dependent variable in (2) takes non-positive values, it will become difficult to transform it if we run into such problems. As a result, we estimated an alternative model, equation (3), using e-commerce outcome/traditional retail outcome as dependent variable and therefore eliminating the negativity in the dependent variable. In equation 3, an $\mathrm{ImpactsRatio_i}$ value of less than one indicates better outcomes for the environment as a result of switching to e-commerce, while an $\mathrm{ImpactsRatio_i}$ value greater than one shows the traditional channel fares better than the e-commerce channel. The two retail channels have equal environmental outcomes when the value of $\mathrm{ImpactsRatio_i}$ is equal to one.

$$\mathrm{ImpactsRatio_i} = \alpha + \beta 1\ \mathrm{LogisticalActivity_i} + \beta 2\ \mathrm{EnvironmentalIndicator_i} + \beta 3\ \mathrm{ProductType_i} + \beta 4\ \mathrm{PopulationDensity_i} + \beta 5\ \mathrm{StudyRegion_i} + \beta 6\ \mathrm{Year_i} + \varepsilon_i \qquad (3)$$

As expected from data gathered from different journal articles and over a long period of time, diagnostics from the regression of equation (3) indicated the presence of heteroscedasticity and non-normality in the dependent variable. Heteroscedasticity poses problems in ordinary least squares (OLS) regressions as it leads to biased standard errors, making statistical tests of significance invalid, even though the estimators will be unbiased. With biased standard errors, one may fail to reject a null hypothesis when the null hypothesis is false. Non-normality of the dependent variable (and hence the idiosyncratic error terms) also leads to similar inference problems, in addition to the OLS standard errors no longer being the most efficient.

Since an attempt to use a log transformation did solve the problem, we used Box-Cox transformation to achieve normal and homoscedastic error terms. The Box-Cox approach, first developed by Box and Cox (1964), is a power transformation that can be used to normalize a dependent variable with non-normal distribution. The Box-Cox takes the following form:

$$y_i^{(\lambda)} = \begin{cases} \dfrac{y_i^{\lambda} - 1}{\lambda} & \text{if } \lambda \neq 0, \\ \ln y_i & \text{if } \lambda = 0, \end{cases} \qquad (4)$$

with lambda (λ) varying from -5 to 5. A value of lambda that results in the best approximation of a normal distribution curve for the dependent variable is selected and this operation can be easily and quickly performed in most econometric software. In the case of the current study, the R software chose 0.3 as the optimal lambda and hence the following equation was estimated:

$$((\text{ImpactsRatio}^{\wedge}\ 0.3) - 1)\ /\ 0.3_{\text{i}} = \alpha + \beta 1\ \text{LogisticalActivity}_{\text{i}} + \beta 2\ \text{EnvironmentalIndicator}_{\text{i}} +$$

$$\beta 3\ \text{ProductType}_{\text{i}} + \beta 4\ \text{PopulationDensity}_{\text{i}} + \beta 5\ \text{StudyRegion}_{\text{i}} + \beta 6\ \text{Year}_{\text{i}} + \varepsilon_{\text{i}} \quad (5)$$

In the above versions of the model, the impact of a particular year could only be explained relative to a reference year which was automatically selected by the R software used for the analysis. It is possible that the relative environmental impacts of e-commerce over traditional channels may have changed over time, for example, due to e-commerce economies of scale and improvements in technology. To investigate if there is a time trend, we re-estimated equation (5) by using the "year" variable as ordinal rather than categorical.

2.3 Results

Table 4 presents the meta-analysis regression results of the Relative Impact variable, which is the percentage environmental impact of e-commerce over traditional retail channels for the various environmental indicators. Since all the regressors are categorical variables, the coefficients of the categorical independent variables estimate the effects of a category relative to a reference case, with the reference case automatically selected by the R software used to conduct the analysis. For all the successive regressions in this study, the reference cases are life-cycle for logistical activity, CO_2-eq for environmental indicator, desktop PC for product type, rural for population density, Asia for study region and 2000 for the year variable. As a result, the coefficients estimate the ceteris paribus impact of a particular category on the environmental impacts of e-commerce over traditional retail channels, relative to a base case involving the *life-cycle CO2-eq emissions of desktop PC that was sold in rural Asia in the year 2000* (the reference case).

From Table 4, there are three explanatory variables that are statistically significant: packaging phase, region Europe and region North America. The coefficient estimates are positive with magnitudes ranging from 1.97 for North America to 3.96 for Europe. Note that the unit of the Relative Impact variable is percent and is equal to (environmental impact of e-commerce/environmental impact of traditional retail - 1) *100, meaning negative values of the Relative Impact indicate better environmental outcomes for the e-commerce option, while positive values show greater environmental damages. As a result, a regressor with a positive coefficient increases the value of the Relative Impact variable and indicates a deterioration of environmental outcomes as the retail channel switches from traditional brick and mortar to e-commerce.

Table 4: Meta-analysis results for Relative Impact (equation 2)

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	-0.65889	1.23715	-0.533	0.596032	
Logistical_ActivityOther	-0.72585	0.53484	-1.357	0.179165	
Logistical_ActivityPackaging	2.50258	0.46459	5.387	9.38e-07	***
Logistical_ActivityTransportation	-0.04683	0.42147	-0.111	0.911852	
Environmental_IndicatorEnergy Use	-0.01791	0.39260	-0.046	0.963754	
Environmental_IndicatorOther	0.13467	0.52143	0.258	0.796967	
Environmental_IndicatorWaste	0.37055	0.53135	0.697	0.487913	
ProductDVDs	-2.39421	2.83448	-0.845	0.401211	
ProductOther	-3.21051	2.03483	-1.578	0.119190	
ProductPaper book	1.84259	2.06843	0.891	0.376124	
Population_DensitySuburban	0.56031	0.84082	0.666	0.507386	
Population_DensityUnknown	-1.30242	0.88065	-1.479	0.143712	
Population_DensityUrban	1.51719	0.84082	1.804	0.075529	.
RegionEurope	3.96087	1.69566	2.336	0.022410	*
RegionNorth America	1.96884	0.55238	3.564	0.000667	***
Year2001	-3.85438	2.19252	-1.758	0.083187	.
Year2002	-1.13495	2.24398	-0.506	0.614628	
Year2004	-0.66397	2.35243	-0.282	0.778597	
Year2005	-2.33313	1.18864	-1.963	0.053695	.
Year2007	0.13609	2.97404	0.046	0.963634	
Year2009	1.40842	2.21610	0.636	0.527179	
Year2010	-1.55495	2.87855	-0.540	0.590810	
Year2011	-5.93713	3.57959	-1.659	0.101734	
Year2012	-2.47183	3.04962	-0.811	0.420418	
Year2013	-2.56511	2.54914	-1.006	0.317805	
Year2015	-1.98866	3.08436	-0.645	0.521223	
Year2018	1.22569	3.00667	0.408	0.684789	
Year2020	0.14822	2.26483	0.065	0.948009	

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

The intercept, which represents the estimated mean value of the percentage environmental impacts of e-commerce over traditional retail channels for the reference group is not statistically significant, indicating that switching to e-commerce did not have any impact on the life-cycle CO2-eq emissions of desktop PC sold in rural Asia in the year 2000. Since the coefficients for other years, other environmental indicators (energy use, waste, etc.), other products (DVDs, books etc.) and other population density types (urban, suburban, unknown) are not statistically significant, this also means that on a life-cycle basis, switching from traditional retail to e-commerce did not have an impact on any of the environmental indicators for the experiments conducted in Asia.

For experiments conducted in Europe and North America, the coefficients are positive and significant at the 95% and the 99.9% confidence levels respectively. The meta-analysis in Table 4 shows that, relative to experiments conducted in Asia, the life-cycle environmental damages of e-commerce over the traditional channel increase by 3.96% and 1.97% for Europe and North America respectively. Similarly, the positive coefficient for the packaging activity indicates that relative to a life-cycle analysis, considering the packaging phase alone increases environmental damages by 2.5% as the retail channel switches from traditional to e-commerce.

Figure 7: Model diagnostics for equation 2 regression

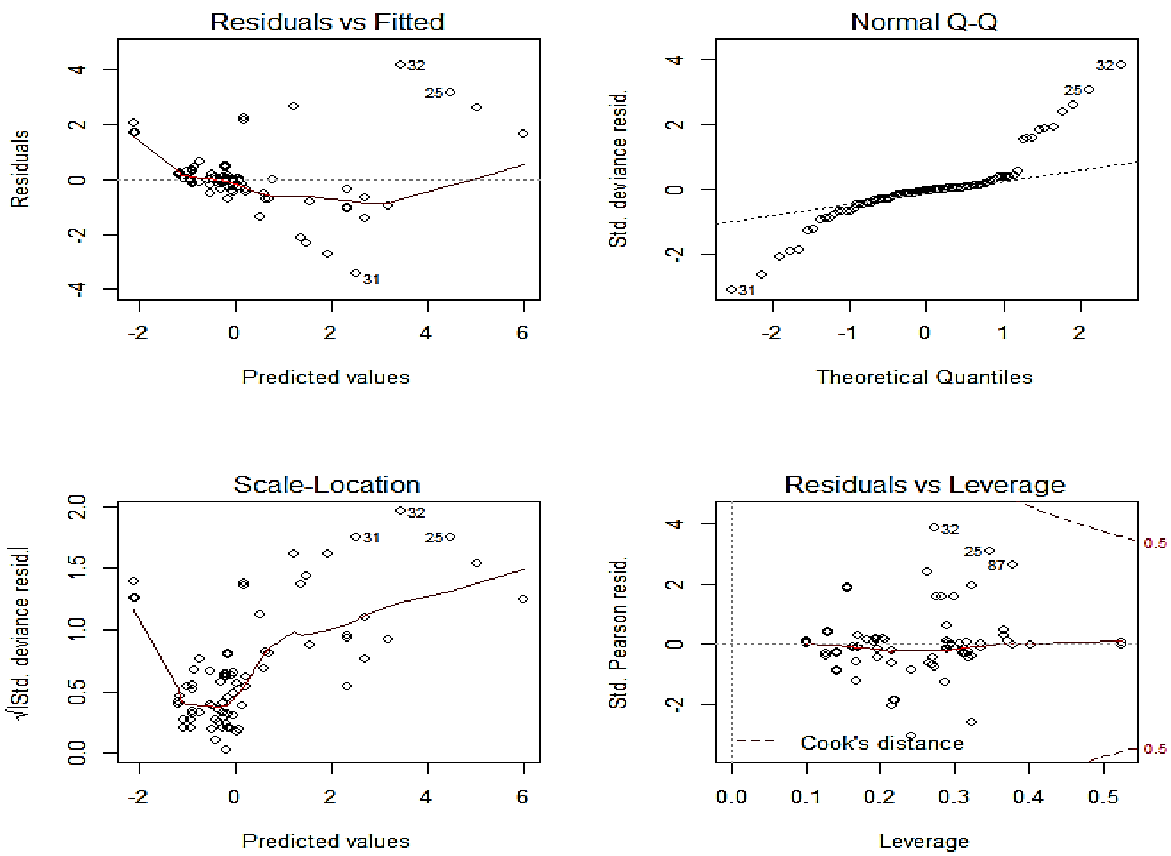


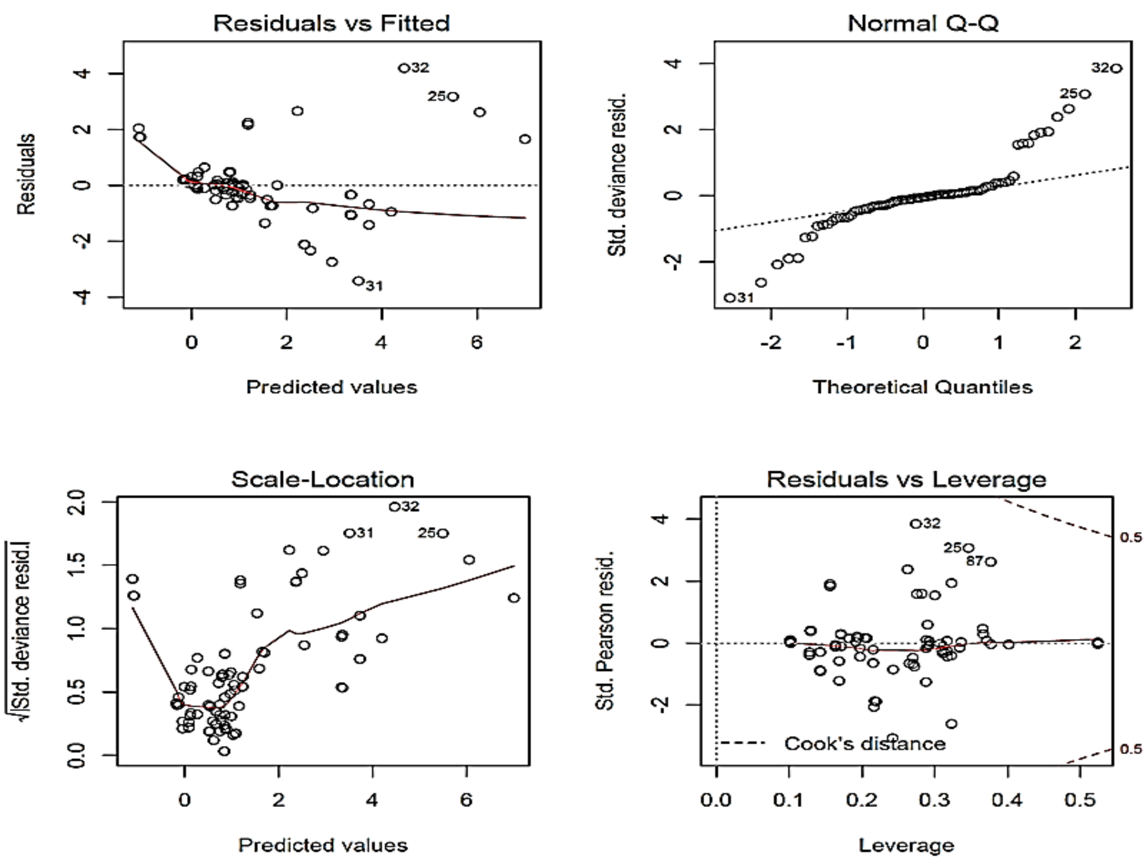
Figure 7 shows the model diagnostics for regression equation 2. As shown in the top left panel (residual vs fitted), the predicted values were generally higher than the observed values as many of the dots are below the zero line. The residual variance also gets larger as the predicted value increases (scale-location, bottom left panel), suggesting the presence of heteroskedasticity. In the top right panel, the residual variance increases along the Normal Q-Q line but curves off at both ends. Normal Q-Q plots exhibiting such behavior generally indicate data that have more extreme values than would be expected if it truly came from a normal distribution. Finally, the bottom right panel (residuals vs leverage) which helps identify influential outliers shows no observation outside of the dashed line (Cook's distance), pointing to no influential observation in the data.

Table 5: Meta-analysis results for Impacts Ratio (equation 3)

```
Coefficients:
                                    Estimate Std. Error t value Pr(>|t|)    
(Intercept)                          0.33855    1.23722   0.274 0.785180    
Logistical_ActivityOther            -0.72713    0.53487  -1.359 0.178431    
Logistical_ActivityPackaging         2.50114    0.46462   5.383 9.51e-07 ***
Logistical_ActivityTransportation   -0.04625    0.42149  -0.110 0.912933    
Environmental_IndicatorEnergy Use   -0.01696    0.39262  -0.043 0.965672    
Environmental_IndicatorOther         0.13333    0.52146   0.256 0.798961    
Environmental_IndicatorWaste         0.37171    0.53138   0.700 0.486578    
ProductDVDs                         -2.38454    2.83463  -0.841 0.403132    
ProductOther                        -3.20324    2.03493  -1.574 0.120034    
ProductPaper book                    1.84374    2.06854   0.891 0.375852    
Population_DensitySuburban           0.56038    0.84086   0.666 0.507356    
Population_DensityUnknown           -1.30070    0.88070  -1.477 0.144254    
Population_DensityUrban              1.51904    0.84086   1.807 0.075196 .  
RegionEurope                         3.96230    1.69575   2.337 0.022370 *  
RegionNorth America                  1.96956    0.55241   3.565 0.000665 ***
Year2001                            -3.85389    2.19263  -1.758 0.083242 .  
Year2002                            -1.13674    2.24410  -0.507 0.614089    
Year2004                            -0.66994    2.35256  -0.285 0.776673    
Year2005                            -2.33258    1.18870  -1.962 0.053763 .  
Year2007                             0.12936    2.97420   0.043 0.965434    
Year2009                             1.40086    2.21622   0.632 0.529414    
Year2010                            -1.56480    2.87871  -0.544 0.588484    
Year2011                            -5.93706    3.57978  -1.659 0.101756    
Year2012                            -2.47586    3.04978  -0.812 0.419688    
Year2013                            -2.56644    2.54928  -1.007 0.317582    
Year2015                            -1.99166    3.08452  -0.646 0.520619    
Year2018                             1.21630    3.00683   0.405 0.687087    
Year2020                             0.14201    2.26495   0.063 0.950189    
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

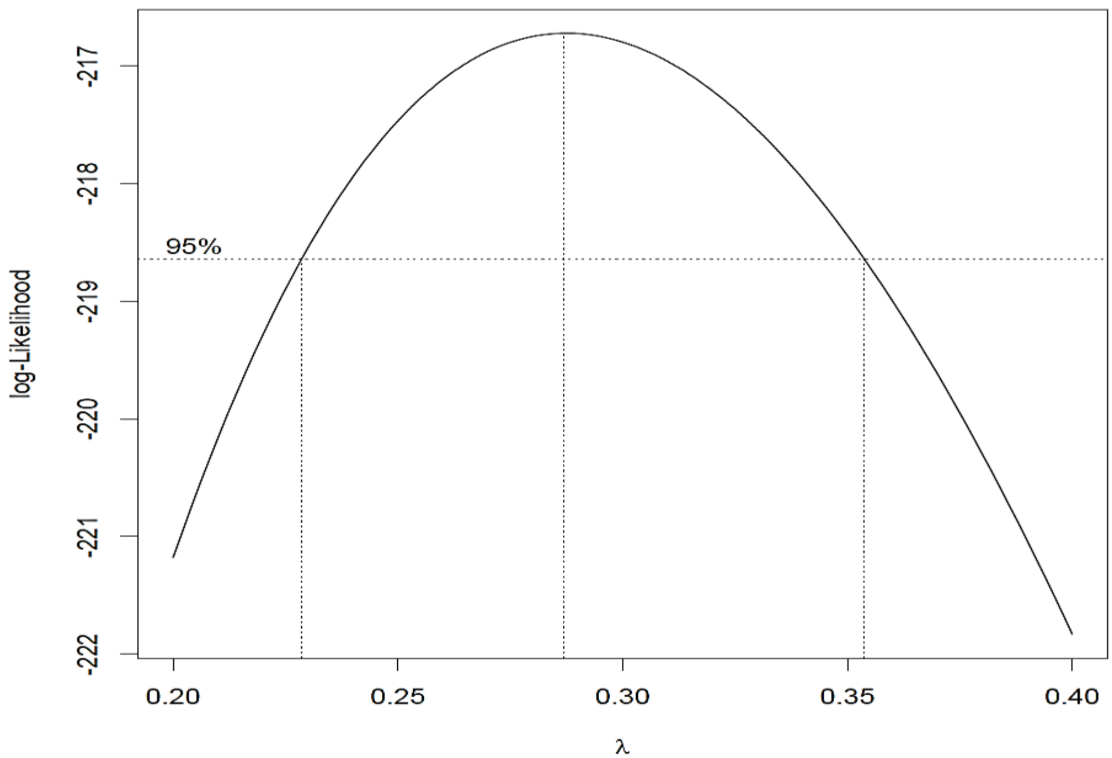
The presence of heteroscedasticity and non-normality calls for a transformation of the dependent variable. However, since the dependent variable takes non-negative values, it limits the pool of transformation options that one can use. A prime example would be a log transformation of the data which would be impossible given the negative values. To overcome this, we first estimated an alternative model (equation 3), using e-commerce environmental outcomes divided by the traditional retail outcomes (Impacts Ratio) as the dependent variable, therefore eliminating the negativity in the dependent variable. An Impacts Ratio value of less than one indicates better environmental outcomes as a result of switching to e-commerce, while a value greater than one shows the traditional channel fares better than the e-commerce channel.

Figure 8: Model diagnostics for equation 3 regression



As shown in table 5, the regression result for the Impacts Ratio variable (equation 3) is similar to the result for Relative Impact variable (equation 2). The packaging activity, region Europe and region North America continue to be statistically significant. However, heteroscedasticity and non-normality are still present in the transformed data (Figure 8).

Figure 9: Box-Cox transformation of ImpactsRatio: the optimal lambda



Since an attempt to use a log transformation did not solve the problem, we applied a Box-Cox transformation on the ImpactsRatio variable to achieve normal and homoscedastic error terms (equation 4). The R software chose 0.3 as the optimal lambda that results in the best approximation of a normal distribution curve for the dependent variable (Figure 9). Figure 10 shows the model diagnostics for the regression using the Box-Cox transformed data, and as shown, the transformation resulted in normal and homoscedastic error terms.

Table 6: Meta-analysis results for ImpactsRatio (equation 4, Box-Cox transformation)

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	-0.34824	0.82778	-0.421	0.675	
Logistical_ActivityOther	-1.71586	0.35787	-4.795	9.05e-06	***
Logistical_ActivityPackaging	1.38146	0.31086	4.444	3.29e-05	***
Logistical_ActivityTransportation	-0.26157	0.28200	-0.928	0.357	
Environmental_IndicatorEnergy Use	-0.04295	0.26269	-0.164	0.871	
Environmental_IndicatorOther	0.12001	0.34889	0.344	0.732	
Environmental_IndicatorWaste	0.16188	0.35553	0.455	0.650	
ProductDVDs	0.05531	1.89656	0.029	0.977	
ProductOther	-1.23121	1.36151	-0.904	0.369	
ProductPaper book	1.24191	1.38400	0.897	0.373	
Population_DensitySuburban	0.33901	0.56260	0.603	0.549	
Population_DensityUnknown	0.17208	0.58925	0.292	0.771	
Population_DensityUrban	0.37669	0.56260	0.670	0.505	
RegionEurope	1.87169	1.13458	1.650	0.104	
RegionNorth America	0.57827	0.36960	1.565	0.122	
Year2001	-1.82915	1.46703	-1.247	0.217	
Year2002	-1.03685	1.50146	-0.691	0.492	
Year2004	-1.80720	1.57403	-1.148	0.255	
Year2005	-1.09798	0.79532	-1.381	0.172	
Year2007	-1.05139	1.98995	-0.528	0.599	
Year2009	0.59620	1.48281	0.402	0.689	
Year2010	-2.37151	1.92606	-1.231	0.222	
Year2011	-3.34033	2.39512	-1.395	0.168	
Year2012	-2.09798	2.04052	-1.028	0.307	
Year2013	-0.90969	1.70565	-0.533	0.596	
Year2015	-1.10730	2.06376	-0.537	0.593	
Year2018	-0.21070	2.01178	-0.105	0.917	
Year2020	0.01155	1.51541	0.008	0.994	

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

With the Box-Cox transformation the significance of e-commerce packing as an environmentally damaging activity continues to stand out (Table 6). In addition, 'Other' activities, which mostly reflect the production phase become significant, but with a negative coefficient. This result suggests that relative to a life-cycle analysis, “other” supply chain activities (mostly production, but excluding transportation and packaging) fare better for the environment as the retail channel switches from the traditional brick and mortar store to e-commerce. However, one key difference between the results for the model using the Box-Cox transformed data and the preceding regression models is that the significance of Europe and North America regions relative to Asia no longer holds.

Figure 10: Model diagnostics for equation 4 regression

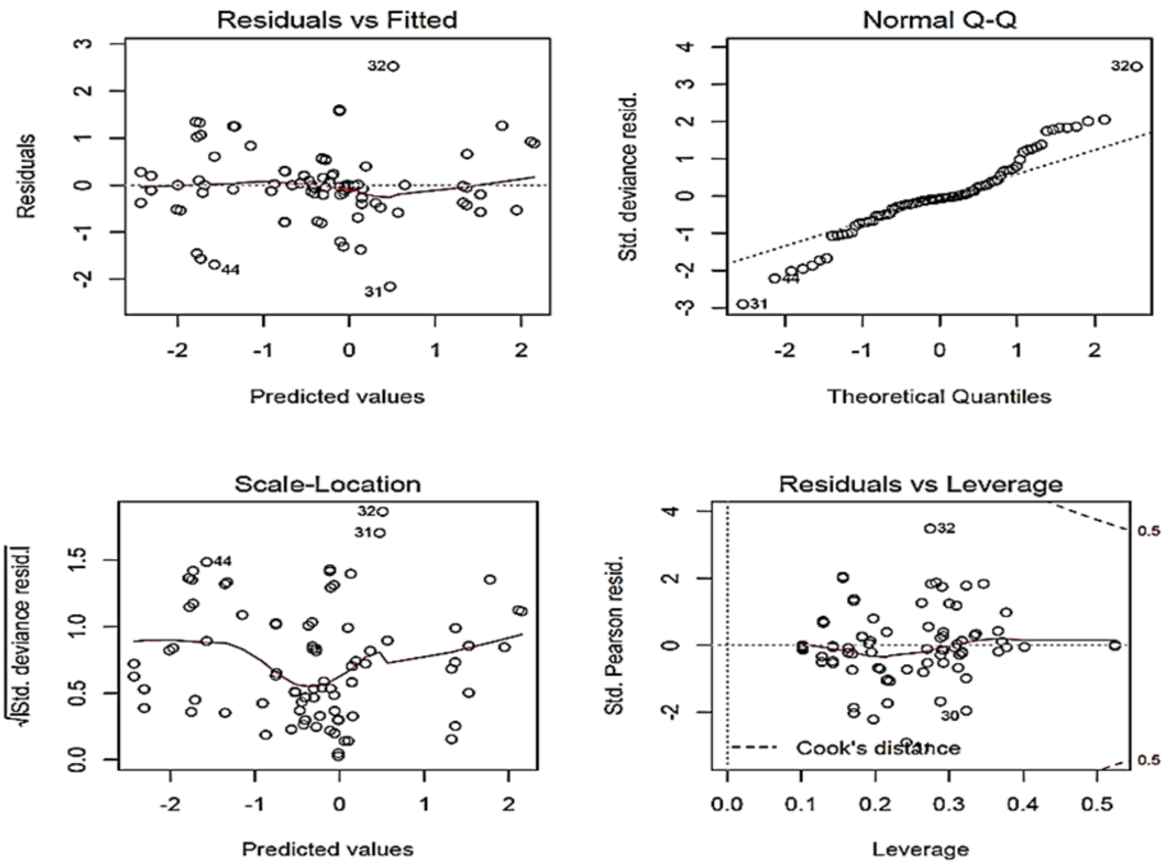


Table 7: Meta-analysis results for ImpactsRatio (equation 4, ordinal "year" variable)

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	-88.72473	56.90846	-1.559	0.1229	
Logistical_ActivityOther	-1.59869	0.36544	-4.375	3.59e-05	***
Logistical_ActivityPackaging	1.52687	0.31761	4.807	6.94e-06	***
Logistical_ActivityTransportation	-0.02708	0.24912	-0.109	0.9137	
Environmental_IndicatorEnergy Use	0.20837	0.25969	0.802	0.4247	
Environmental_IndicatorOther	0.09580	0.32922	0.291	0.7718	
Environmental_IndicatorWaste	0.19612	0.37178	0.528	0.5993	
ProductDVDs	-0.92730	0.43569	-2.128	0.0363	*
ProductOther	-0.56711	0.42878	-1.323	0.1897	
ProductPaper book	0.41624	0.33686	1.236	0.2202	
Population_DensitySuburban	0.18700	0.51531	0.363	0.7176	
Population_DensityUnknown	0.57559	0.58225	0.989	0.3258	
Population_DensityUrban	-0.43074	0.54463	-0.791	0.4313	
RegionEurope	-0.19391	0.47896	-0.405	0.6866	
RegionNorth America	-0.07178	0.34187	-0.210	0.8342	
Year	0.04400	0.02841	1.549	0.1253	

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

In the versions of the regression model analyzed so far, the impact of a particular year could only be explained relative to a reference year which was automatically selected by the R software used for the analysis. To investigate if the reported impacts change over time, that is, the presence of a general time trend due to, for example, e-commerce economies of scale and improvements in technology, we investigated a final version of our model where we used the "year" variable as ordinal rather than categorical. The results remain robust (Table 7), and we fail to reject the null hypothesis that the environmental impacts of e-commerce relative to the traditional retail channel do not exhibit a time trend.

2.4 Discussion

Based on the meta-analysis, we find a couple of key results. First, on a life-cycle basis, switching from traditional retail to e-commerce did not have a statistically significant impact on the environment. We conclude this result from the intercept, which represents the estimated mean value of the environmental impacts of e-commerce over traditional retail channels for the reference group, and the fact that almost all categories outside the reference group are not statistically significant. Secondly, we confirm the results of the systematic literature review that e-commerce packaging is an environmentally damaging activity.

In all the different regression versions we run and after controlling for the different study characteristics, the reputation of e-commerce packaging as an activity that negatively affects the environment continues to stand out. This environmental damage is attributed to the fact that the packaging system for products sold in conventional stores differs from those sold online. As an example, a book sold online may require an individual package while it can be sold without a package at the regular bookstore. The environmental damage from packaging is even more pronounced when cardboard packaging is utilized.

The existing body of literature on which this meta-analysis is based covers a wide range of cases, from books to DVDs and provides several indicators to illustrate the impacts of e-commerce on the environment. In their review of 56 papers published between 2001 and 2014, Mangiaracina et al. (2015) find that about 20% of the reviewed papers address the 'packaging' theme, which speaks to the importance of e-commerce packaging from a sustainability perspective. Their findings indicate that, from a product-packaging standpoint, e-commerce is generally thought to affect the environment negatively due to the individual packaging required to ship a few products to the customer. The exception is when physical products such as music disks are replaced by online downloads, the impact of e-commerce on the environment largely becomes positive, as no packaging is required – an exception being multiple streaming of the same content which may lead to more environmental damages (Nair et al. 2019).

Focusing on energy use, Pålsson et al. (2017) conducted a structured literature review and a content analysis to determine factors affecting the relative energy efficiency of e-business and traditional trade. Analyzing specific cases within the studies, the study finds that the additional packaging required under e-commerce channels led to significantly higher energy consumption and hence possibly larger environmental damage. Van Loon et al. (2015), in their analysis of greenhouse gas emissions from online retailing of fast-moving consumer goods, argue that e-commerce can be made more environmentally friendly by encouraging consumers to maximize the basket size as well as utilizing less energy-intensive packaging systems. According to the study, "100 g of corrugated cardboard plus limited amounts (33 g in total) of filling material, results in 181 g CO2-eq per item" (Van Loon et al. 2015, p. 484) compared to shopping bags in conventional trade that results in about 11 g CO2-eq. As a result, the environmental impact of shopping bags used in traditional stores is far lower due to the limited amount of packaging used.

In their report on the environmental analysis of US Online Shopping, the Massachusetts Institute of Technology (MIT) Center for Transportation and Logistics provides a detailed comparison of the carbon footprint of e-commerce versus traditional retailers. Based on life-cycle analysis, they find that, unlike the traditional brick and mortar stores where shoppers' travel is the main source of emissions, packaging is the main source of greenhouse gas emissions for online retailing businesses. These tangible differences in the sources of carbon footprint are attributed to the additional shipment packaging, which includes only pallets and protective wraps for traditional stores but comprises cardboard boxes and foam peanuts for online retailing.

In the first chapter of this thesis, we conducted a more comprehensive systematic review that provided an up-to-date understanding of the net environmental impacts of e-commerce over traditional retail. We found that energy consumption, CO_2-eq emissions and hazardous waste production in the packaging stage are shown to be higher in the e-commerce system than in the traditional system. The results of our systematic review and the current meta-analysis confirm and support the conclusions of earlier studies that e-commerce packaging is an environmentally damaging activity.

2.5 Conclusion

In the first chapter, we conducted a systematic review that provided a more general understanding of the net environmental impacts of e-commerce over traditional retail. We found that e-commerce generally tends to have positive impacts on the environment, except at the packaging phase. As the results were based on a simple univariate analysis of the difference in impacts between e-commerce and traditional retail, they were not reflective of the true net environmental impacts of e-commerce on the environment. The meta-analysis in this study attempted to address this limitation by estimating several successive regression analyses that controlled for the different study characteristics; for example, differences in the type of product studied, study region, population density, type of logistical activity assessed and the year of study.

Based on the regression analysis, we make two conclusions. First, on a life-cycle basis, switching from traditional retail to e-commerce does not seem to have any statistically significant impact on the environment. Secondly, we confirm the results of our systematic literature review that e-commerce packaging is an environmentally damaging activity. The reason e-commerce fares badly environmentally at the packaging stage over the traditional retail channel is likely related to the fact that packaging requirements are greater in the e-commerce system, given the vast number of small orders that need to be individually shipped. In addition, packaging used in e-commerce channels tends to be corrugated cardboard boxes which has implications for environmental sustainability in terms of the energy required to produce them.

Chapter Three

An Aggregate Empirical Investigation of the Impact of E-commerce on Energy Consumption Using Empirical Dynamic Models

3.1 Introduction

This chapter utilizes Empirical Dynamic Models (EDM) to investigate the impacts of e-commerce on energy consumption. Based on mathematical theory developed by Takens (1981), EDM is a novel data-driven methodology that can be applied to complex dynamic systems. One characteristic of complex dynamic systems is that they exhibit non-linear relationships which are difficult to study using traditional linear statistical techniques that are centered around a hypothesized correlation between different variables. In naturally occurring dynamic systems, correlation between different variables changes over time, or with different states of the system.

There is acknowledgment among the existing body of literature that the interaction within the e-commerce-energy-environment system is complex, chaotic, and scale-dependent, which makes estimating any impacts very difficult. Even with macroeconomic data, Dost, and Maier (2017) assert that the effect of ecommerce on energy use and environmental outcomes may have changed continually as e-commerce gained traction, making standard linear macroeconomic models unsuitable for such state-dependent effects. In order to model the complex e-commerce-energy-environment system in the standard parametric models, one would have to specify all the variables and perceived relationships. Dost and Maier (2017, p. 801) note that given the "vast number of economic, social, or physical variables that conceivably could exert influence" on the -commerce-energy-environment system, it will be difficult to come up with a specification that truly models the impact of e-commerce on energy use and the environment.

On the other hand, EDM can, with limited assumptions, deduce the behavior of a system, thanks to Takens' (1981) proof that the underlying dynamics of a system can be recovered just from the lagged coordinates of a single time series that is part of the system. This study applies EDM to time series macroeconomic data to draw conclusions on the impact of increased e-commerce penetration on energy consumption. Specifically, the study utilizes monthly energy consumption in various sectors of the Canadian economy (residential, commercial, industrial and transportation), along with the share of e-commerce sales in overall Canadian retail sales. Dost and Maier (2017) used United States (U.S.) data to conduct a similar analysis, but the current study applies the approach to Canadian data to investigate the existence of nonlinear e-commerce-energy consumption and estimate state-dependent marginal effects.

The results show that e-commerce did not influence Canadian residential, commercial, and industrial natural gas consumption over the 2016-2021 period. Rather, convergent cross-mapping CCM causality test confirmed causal forcing from e-commerce to Canadian motor gasoline and distillate fuel consumption for the 2019-2021 period where monthly consumption data was available. On average, Canadian motor gasoline and distillate fuel consumption decreased by 1.0% and 2.3% respectively for every additional percentage point increase in retail e-commerce sales.

3.2 Literature Review

Ever since Takens (1981) proved that the dynamics of an underlying system can be recovered just from a single time series variable, EDM has been used in multiple applications. Variants of EDM have been used to characterize and understand nonlinearity in human heart rhythms (Sugihara 1994, Sugihara et al. 1996), fish populations (Dixon et al. 1999) and marine copepods dynamics (Liu et al. 2014). Hsieh et al. (2005) have also used it to test for nonlinear dynamics in large-scale marine data from the North Pacific Ocean.

Sugihara et al. (2012) first introduced (CCM), an EDM variant analogous to Granger causality test (Granger 1969), to identify causal interactions between two variables from the same system and applied it to the sardine-anchovy-temperature problem in the Pacific. Since then, CCM has been used to investigate causal links between climate variables and Pacific Sardine (Deyle et al. 2013), temperature and greenhouse gas concentrations (Van Nes et al. 2015) and cosmic rays and global warming (Tsonis et al. 2015). These experiments were conducted after Deyle and Sugihara (2011) generalized Takens' results to show how multiple time series embedding can better recover the dynamics of a system they are part of.

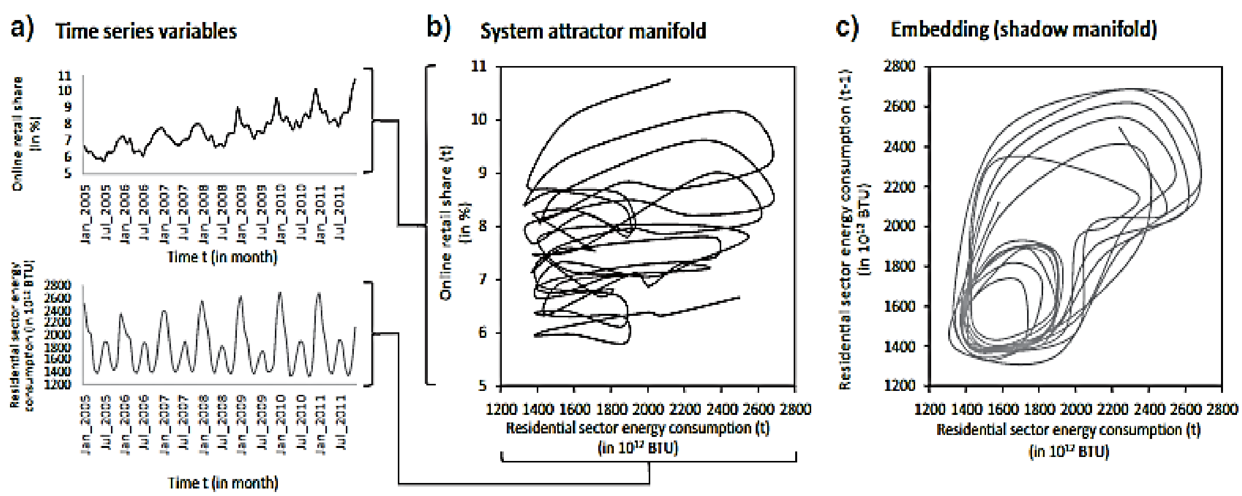
EDM has also been used to detect causal links from short ecological time series data (Hsieh et al. 2007, Ma et al. 2014, Clark et al. 2015) and found to even perform better than conventional methods (Ma et al. 2014). It has been used to distinguish noise in chaotic data from measurement and other external noises (Sugihara and May 1990, Hsieh et al. 2005). Deyle et al. (2016) demonstrated how S-maps, an EDM variant analogous to estimating time-dependent effects in dynamic linear models, can be utilized to estimate state-dependent interaction coefficients between variables within a system.

Beyond ecological data, EDM has also been applied to economic and environmental data. Huffaker and Fearne (2014) investigated dynamic causal interaction between promotions and sales of a beer brand in England and found that the investigated data come from a nonlinear deterministic process, rendering the use of Granger causality unsuitable. Dost (2015) examined causal links between marketing channel system structure and economic variables and found that shocks to channel structure impact economic growth, whereas the former is robust in the face of economic shocks. Like the current analysis, Dost and Maier (2017) used U.S. macroeconomic data to investigate links between e-commerce and energy consumption. The study found that e-commerce positively affects energy consumption in the residential and commercial sectors, while the impacts on the industrial and transportation sectors are negative, albeit less pronounced.

3.3 Methodology

Unlike parametric models which utilize hypothesized equations, EDMs can, with limited assumptions, deduce the behavior of a dynamic system from the time series data. This approach overcomes the impracticality of specifying explicit equations for data whose underlying system is complex (composed of many interacting components), chaotic (deterministic but sometimes appears random) and non-linear (time and state dependent interactions). In EDM, a system is a manifold in a multidimensional system state space rather than just a set of time series variables. The concept of a "state" in EDM is an n-dimensional vector where the coordinates represent the interacting system variables. Over time, the state of the system evolves according to underlying dynamics and forms a trail, with the collection of the trails creating a geometric object referred to as an attractor manifold (see Figure 11 adopted from Dost and Maier (2017)).

Figure 11: The Concepts of a time series, system attractor manifold and shadow manifold



Adopted from Dost and Maier (2017): (a) Two time series variables are used to construct (b)an empirical system attractor manifold. (c) Using just one time series and its own lag(s), it is possible to reconstruct an embedding (shadow manifold) that retains the system attractor dynamics. BTU = British Thermal Units; t = time.

This attractor manifold then describes the relationships between the system variables, using the proximity between the vectors in a multidimensional system state space to make predictions.

However, according to Takens (1981), one does not need the complete set of variables to construct the attractor manifold as the dynamics of the whole system can be reconstructed from the lags of just a single time series variable. This is what is known as a shadow or embedding manifold (panel C in Figure 11). Takens (1981) proves that, using the appropriate E-dimensional lags, the shadow manifold of a time series preserves the essential mathematical properties of the system that it is part of, and therefore, the dynamics of the whole system can be recovered just from that single time series. The essential specification in EDM is thus the appropriate selection of an embedding dimension E of the shadow manifold.

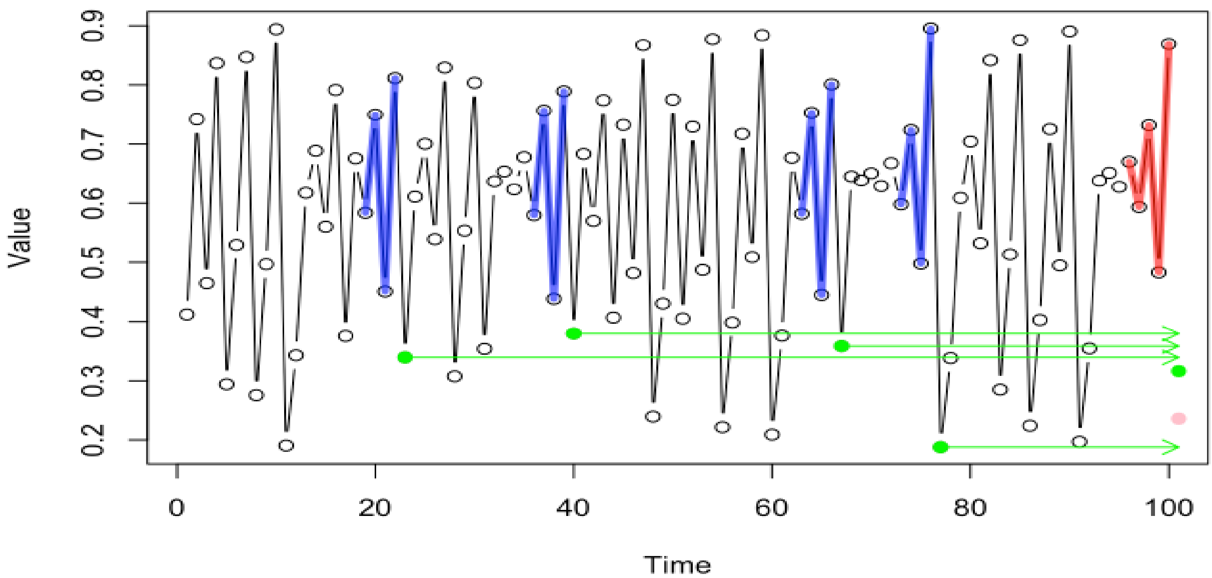
As Dost and Maier (2017) brilliantly illustrate, using EDM to estimate the marginal effects of e-commerce on the environment involves three steps, which have equivalents in standard parametric models. First, an optimal embedding dimension E is empirically selected from the time series data by means of simplex projection, using a univariate EDM model. This is equivalent to specifying a traditional univariate autoregressive model that can provide predictions based on lagged values. The optimal embedding dimension E is the smallest number of lags that maximizes overall univariate predictability and therefore allows one to apply EDM to the variable of interest.

The concept of simplex projection is best explained by Owen Petchey in a 2016 GitHub article[4]. In the example, Petchey (2016) tries to predict the last value in a chaotic time series, i.e., the pink point in Figure 12. First, simplex projection searches for and identifies (through lag selection) dynamics in the past that match the dynamics that occurred just prior to the pink point. In this case, the dynamics of the preceding four data points (red dynamics) closely match four occurrences in the past (blue dynamics). Next, the data points that follow each of the matching

[4] http://opetchey.github.io/RREEBES/Sugihara_and_May_1990_Nature/Simplex_projection_walkthrough.html

blue dynamics; i.e., the green data points are identified. Finally, an Euclidian-distance weighted average of the green data points is calculated to predict the pink data point.

Figure 12: A simplified explanation of the simplex projection method



Source: Petchey (2016)

The second step in the application of EDM is convergent cross-mapping (CCM), an empirical causality test analogous to Granger causality test in the univariate autoregressive model, to assess the influence of the independent variable (i.e. share of e-commerce sales) on the dependent variables (i.e. in our case, Canadian natural gas, motor gasoline and diesel fuel oil consumption). CCM uses cross-prediction correlations to test for causal relationships among the system variables, with the correlations converging to less than zero indicating no causal relationship and convergence to a positive number indicating otherwise. It establishes causality in the reverse direction. For instance, if increased e-commerce share causally affects gasoline consumption, then the e-commerce variable imprints its own signature on to the history of gasoline consumption. As a result, a univariate shadow manifold using the lags of gasoline consumption can reliably predict the values of e-commerce share.

CCM must satisfy two criteria to establish causality: the prediction skill (correlation between predicted and e-commerce share values) must be statistically significant when the full data is used; and it must improve and converge to a number larger than zero as the library size (sample size) increases. If the cross-prediction correlations for e-commerce share from the shadow manifold of the gasoline consumption variable can satisfy the preceding two criteria, then it indicates that e-commerce share has causal influence on gasoline consumption. One advantage of using CCM to test causality is that, unlike Granger causality, it does not require separable stochastic explanatory variables, and this really becomes important as dynamic system variables "typically force, and are forced by, other system variables at the same time, thus violating separability" (Dost and Maier, pp. 5-6, 2017; Sugihara et al. 2012).

As CCM only establishes causal influence and does not provide direction and magnitude of the impacts, a final step is needed to estimate the marginal effects of e-commerce on energy variables. Multi-variate S-maps proposed by Deyle et al. (2016) are used to estimate state-dependent effects (Dost and Maier, 2017; Sugihara et al. 1994, 1996; Dixon et al. 1999), that is, the marginal increase in energy use arising from a unit percentage point increase in the share of e-commerce sales. In terms of technical modelling, we utilized the rEDM R-package developed by Sugihara et al. (2022).

3.4 Empirical Analysis

The data series used in this analysis come from Statistics Canada. The series consist of Canadian monthly natural gas consumption (residential, commercial, and industrial), motor fuel consumption (gasoline and diesel) and percent share of e-commerce retail sales to total retail sales. Data for the predictor variable, the e-commerce percent share, was available only for the period from January 2016 to December 2021 (72 data points) and it therefore limits the length of outcome variables (energy consumption) that can be utilized for the analysis. In addition, monthly data for motor fuel consumption was only available for the period from January 2019 to December 2021, a total of 36 data points. Table 8 provides a descriptive statistics of study dataset.

Table 8: Descriptive statistics of the study data

Variable	Description	Source	Unit	Mean	Standard Deviation
E-commerce retail share	Monthly retail e-commerce sales (unadjusted) divided by monthly retail trade (unadjusted)	Statistics Canada, author calculations	Percent	4.1	2.0
Residential natural gas consumption	Monthly disposition	Statistics Canada	1000 M^3	1,420,874	904,634
Industrial natural gas consumption	Monthly disposition	Statistics Canada	1000 M^3	6,511,130	585,480
Commercial natural gas consumption	Monthly disposition	Statistics Canada	1000 M^3	1,304,982	759,785
Motor gasoline	Monthly disposition	Statistics Canada	M^3	3,429,063	407,416
Distillate fuel oil	Monthly disposition	Statistics Canada	M^3	2,635,722	205,461

Figures 13 and 14 show the evolution of the studied variables over time. As shown, consumption of natural gas in the residential and commercial sectors shows strong seasonality, with the peaks occurring in the winter months when heating is required and troughs in the summer. Consumption of natural gas in the industrial sector shows less cyclicality compared to other sectors, given that natural gas has wider uses beyond heating in the industrial sector, including powering systems and using it as raw material in the production of chemicals and fertilizer.

As shown in Figure 13, on the right-side consumption of motor gasoline and distillate fuel oils show marked decline between the months of March to May 2020, reflecting the onset of the Covid-19 pandemic when lockdown measures were put in place. At the same time, there is a marked increase in the percentage share of retail e-commerce sales to total retail trade (Figure 14) as the stay-at-home measures shifted consumer shopping patterns towards the home delivery option.

Figure 13: Monthly energy consumption, Canada

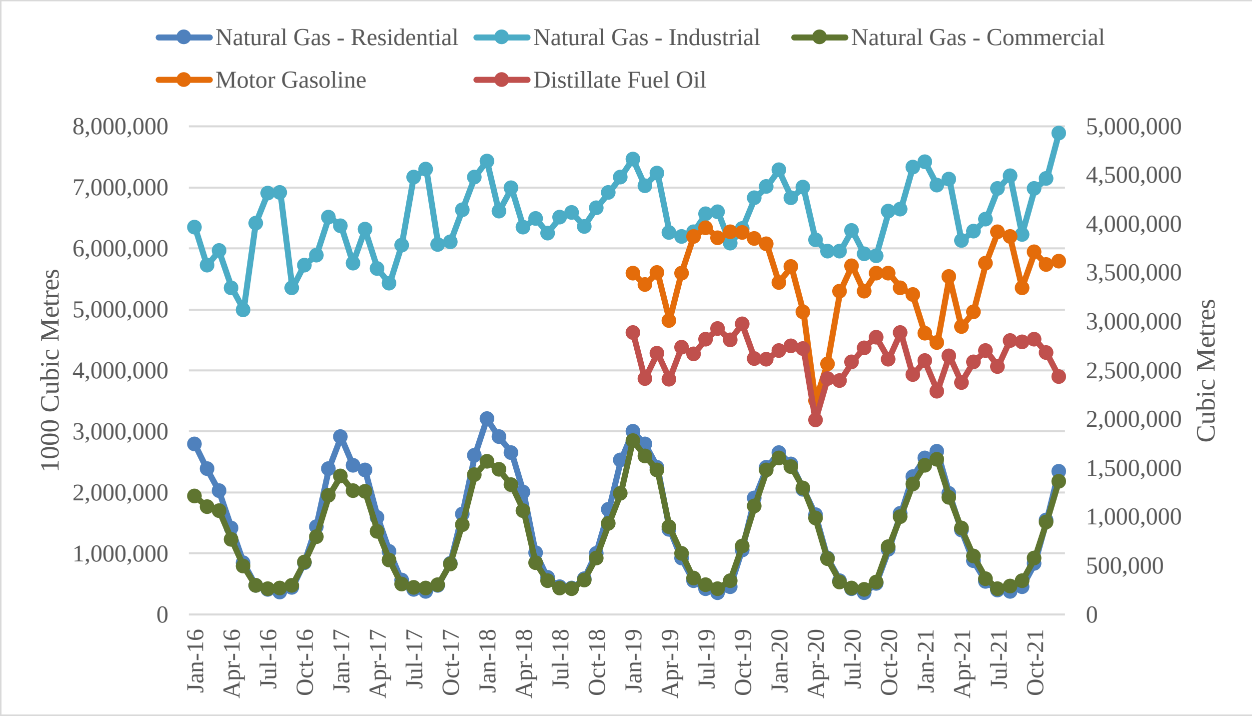
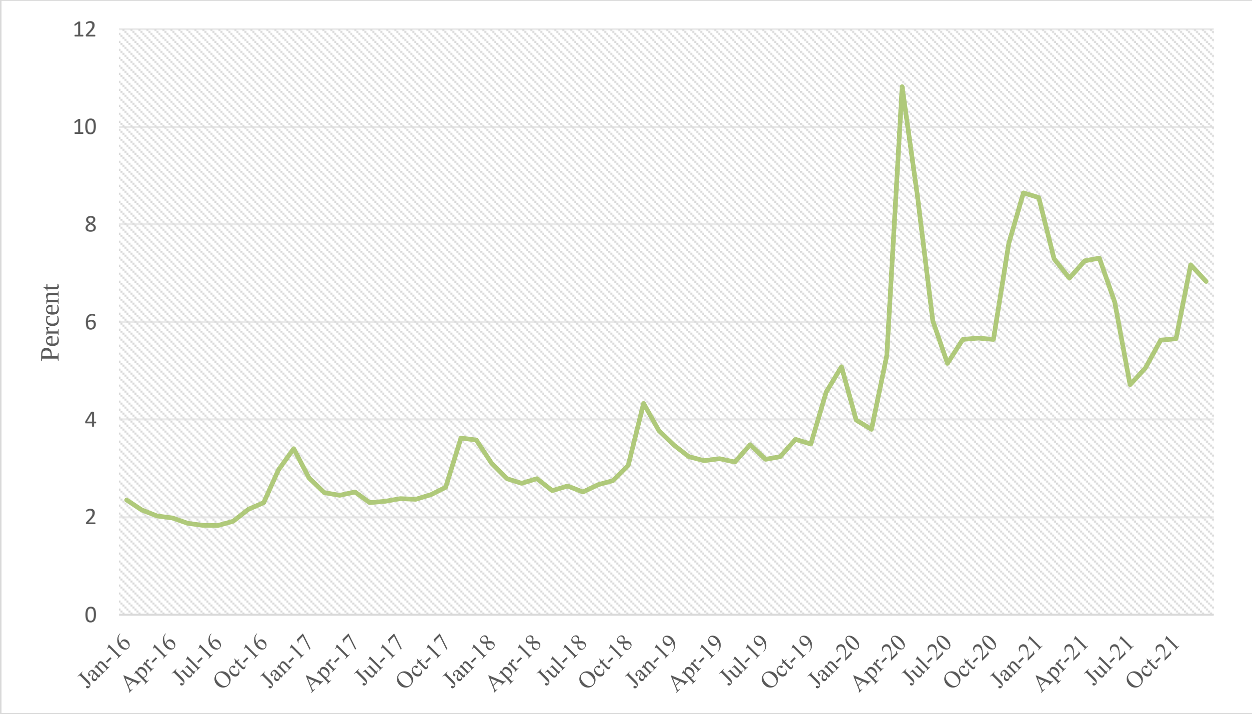


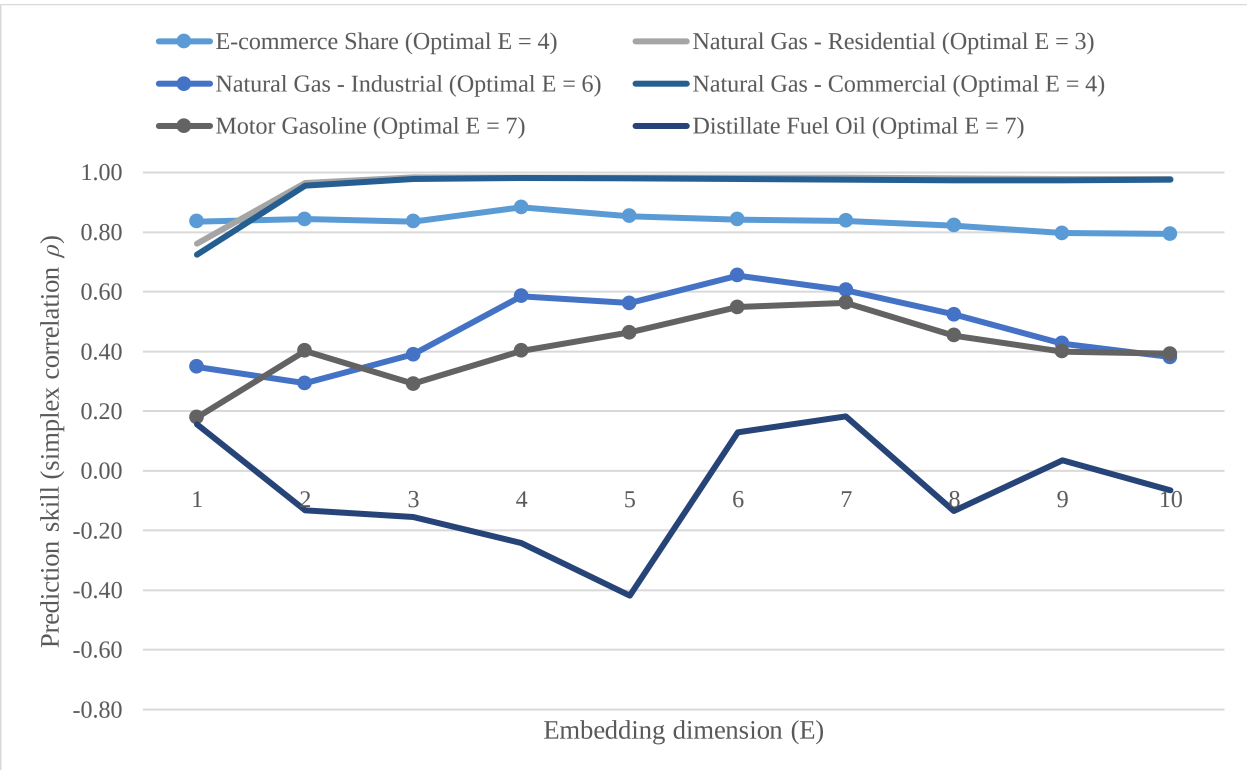
Figure 14: Retail e-commerce as percentage of total retail trade



3.5 Establishing EDM conditions

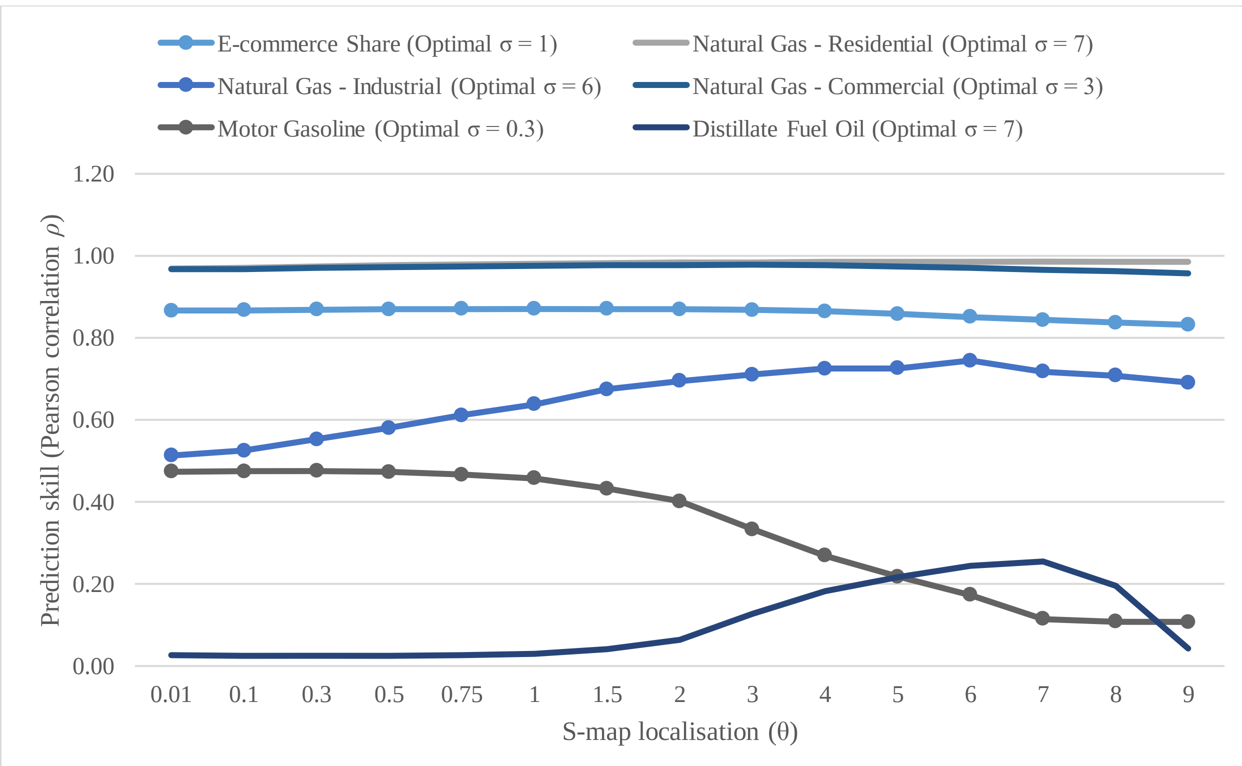
As discussed in the methodology section, EDM is suitable for analyzing complex nonlinear dynamic systems. As a consequence, before utilizing EDM, one needs to ensure that the data analyzed come from such systems, otherwise traditional linear models would be suitable. Two techniques: nearest neighbour prediction using simplex projection and S-map forecasting (Sugihara 1994) were used to identify complex nonlinear behaviour in the underlying process.

Figure 15: Univariate simplex forecast skill versus E for e-commerce and energy use variables



The simplex projection method fits a univariate forecast of a variable onto itself by evaluating prediction skill (ρ) over various lagged coordinates of the variable (embedding dimension E) and chooses an optimal E that maximizes the prediction skill. The prediction skill (ρ) is essentially the Pearson correlation coefficient between actual and forecast values of the variable. To forecast one time step ahead, simplex projection uses a weighted average of nearest neighbours in state-space rather than those close in time. A good univariate predictability shows that a variable comes from a system that exhibits a dynamic behaviour. As shown in Figure 15, the best prediction skill is above 0.65 for all except motor gasoline and distillate fuel consumption, which are likely affected by relatively shorter time series length. As shown, the dynamics of the data are best unfolded when lagged dimensions E are between 3 to 7.

Figure 16: Univariate S-map forecast skill versus θ for e-commerce and energy use variables



The S-map forecasting method utilizes the optimal embedding dimension E and other parameters from the simplex projection to fit local linear maps. This procedure helps us distinguish stochastic behaviour from a nonlinear deterministic one by evaluating the univariate prediction skill (ρ) over the nonlinear localisation parameter, θ, that controls how individual points are weighted when the local linear maps are fitted. Unlike simplex projection that uses nearest neighbours in state-space, the S-map procedure utilizes all available points, with the θ parameter determining how weights are assigned to individual points to localize dynamics.

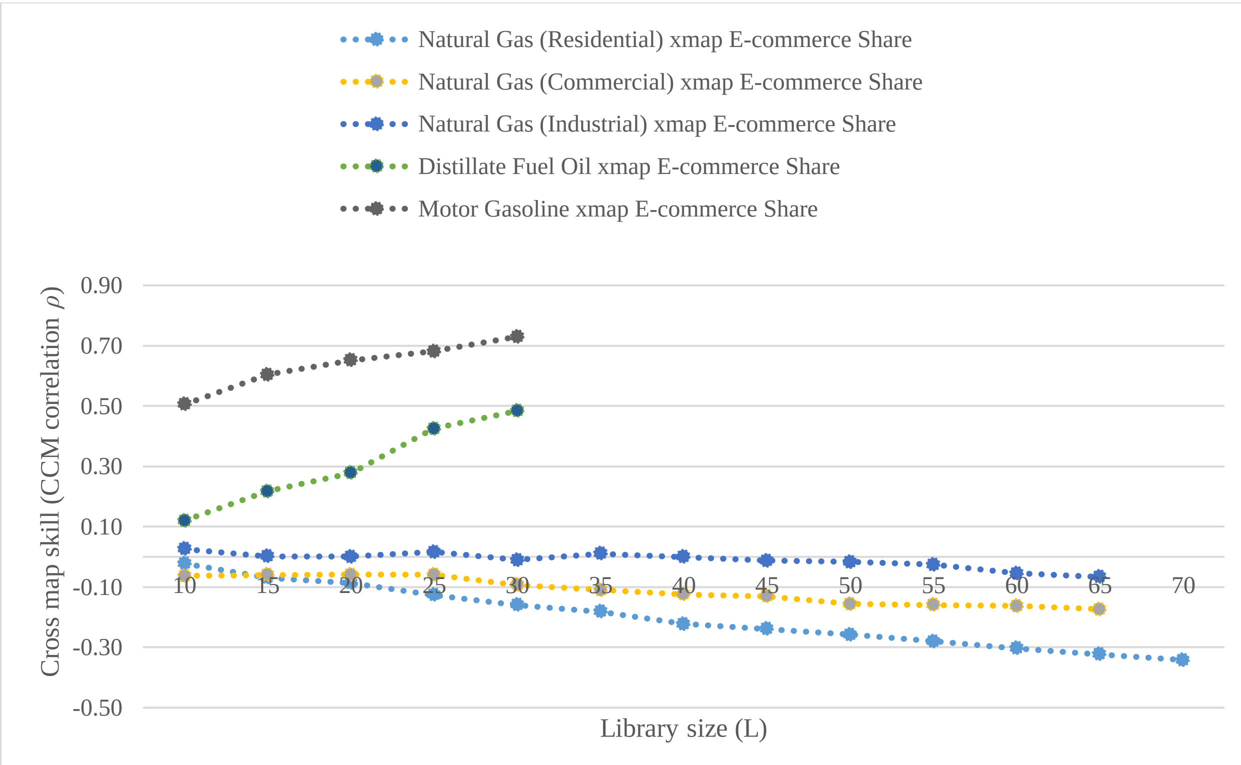
If the localisation parameter $\theta = 0$, all points are assigned equal weights and the local map is no different from the global linear map. As such, traditional linear autoregressive models perform better than EDM. A $\theta > 0$ means points closer in state-space to the predicted point are assigned larger weight such that the local linear map varies depending on the state-space, suggesting nonlinear dynamics of the underlying system. As shown in Figure 16, the e-commerce and energy use variables under investigation exhibit state-dependent behaviour as the θ that maximizes the univariate prediction skill (ρ) is greater than zero for all of them. This result indicates that nonlinear models would fare better than linear autoregressive models, supporting use of EDM to address the current research question.

3.6 Causality Test using CCM.

Given that we have established the conditions for EDM analysis, the next step is to apply CCM, an empirical test analogous to Granger causality, to test for causal forcing between e-commerce share and energy consumption variables. Remember that CCM tests for causality in the reverse direction, i.e., if e-commerce share influences energy consumption, then it will imprint its own history on to the history of energy use variables and hence a lagged coordinate embedding of the influenced variables can reliably predict the values of e-commerce share. In addition, causality is established if the CMM cross-map correlations converge to a positive value.

Figure 17 shows CCM correlation of cross-mapped and observed values over the length of the time series (library size L). The cross-map skill for the natural gas consumption variables deteriorates towards negativity as more time series data is used, indicating e-commerce does not influence natural gas consumption. On the contrary, the cross-map skill for gasoline and distillate fuel consumption improves and converges to a number larger than zero (ρ = 0.73 and ρ = 0.48 respectively) as larger library sizes are utilized. This result confirms that there is causal forcing from e-commerce to motor gasoline and distillate fuel consumption, which will be investigated further in the remainder of the analysis.

Figure 17: Correlation of cross-mapped versus observed value for energy use variables



3.7 Estimating Marginal Effects with S-maps

As noted earlier, CCM only establishes causal influence and does not provide direction and magnitude of the impacts. To estimate the state-dependent marginal effects of e-commerce on gasoline and distillate fuel oil consumption (Δ *energy use* /Δ *e-commerce share*), we will utilize a multivariate S-map method. Unlike the univariate S-map, the multivariate version includes e-commerce share as an additional explanatory variable in the lagged coordinate embeddings of the influenced variables (gasoline and distillate fuel oil consumption), and then evaluates state-dependent marginal effects at the optimal E and θ parameters of the influenced variables.

Figure 18: Marginal effects of e-commerce on fuel consumption at different e-commerce states

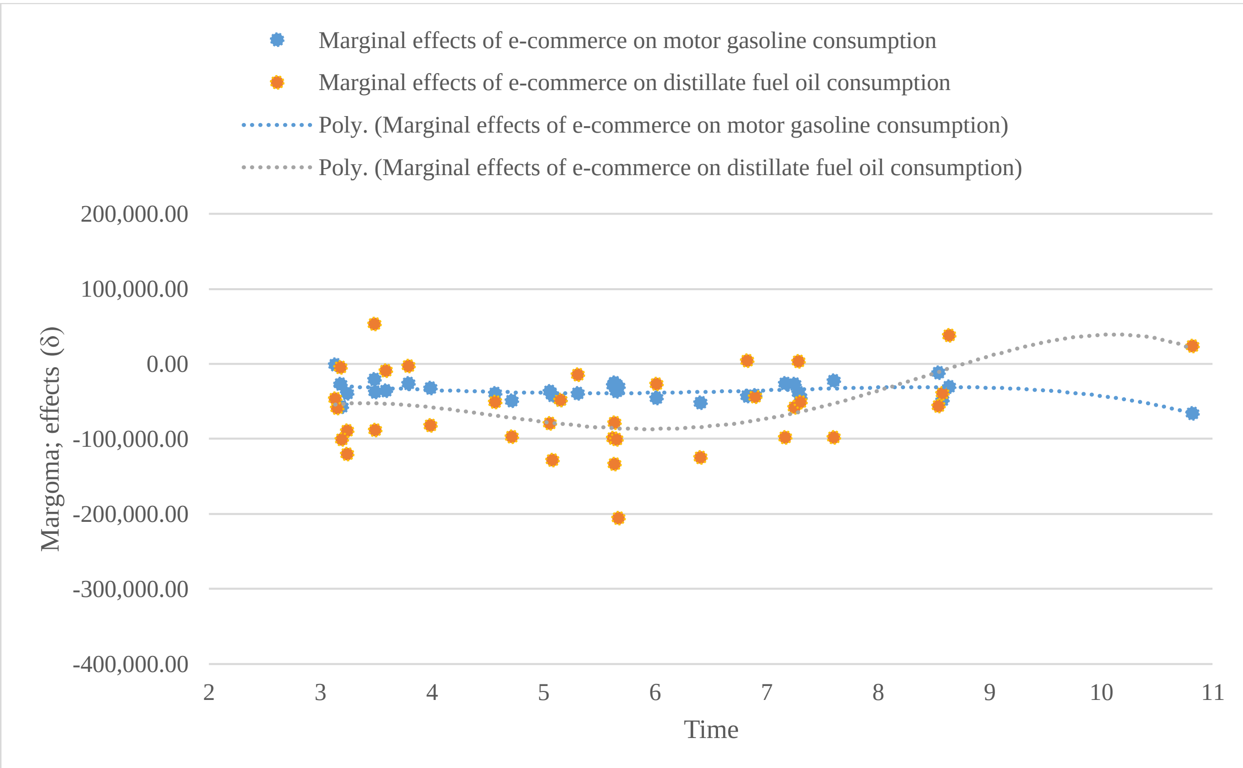


Figure 18 shows a scatterplot of the marginal effects of e-commerce on gasoline and distillate fuel oil consumption at different states of e-commerce penetration levels, fitted with a polynomial curve of order 4. Marginal effects for both variables are largely negative and show state-dependent behaviour, even though the state dependence is weaker for motor gasoline consumption, suggesting near linear impact across all states of e-commerce.

Table 9: Mean marginal effects of e-commerce share on fuel consumption

	2019-2021		2021	
Marginal effect of e-commerce on	Mean (M^3)	Relative change	Mean (M^3)	Relative change
Motor gasoline	(35,522)	-1.0%	(36,520)	-1.1%
Distillate fuel oil	(60,256)	-2.3%	(66,883)	-2.6%

Over the 2019-2021 period, motor gasoline and distillate fuel consumption have, on average, decreased by 35,522 and 60,256 cubic meters respectively for every additional percentage point increase in retail e-commerce sales (Table 9). That represents an average effect of -1.0% and -2.3% for motor gasoline and distillate fuel consumption respectively. The results averaged for the 2021, the most recent year, are similar to the entire period effects.

3.8 Comparison with Other Countries

Dost and Maier (2017) conducted a similar analysis for the U.S. using aggregate sectoral energy consumption. The study found a small decrease (-0.23% in 2015) in U.S. transportation energy consumption for every one percentage point increase in the share of e-commerce in total retail sales. Given this study, we decided to investigate other countries outside North America for which energy consumption and e-commerce data were available and see if the results will hold. Fortunately, the Australian Bureau of Statistics has monthly e-commerce data dating back to 2013, and hence provides more datapoints than Canada. For Asia, Taiwan was the only country where data on monthly e-commerce share, paired with some energy use data, was available. We limited our investigation for these two countries to only the impacts of e-commerce on motor gasoline and diesel consumption in order to compare with results for Canada, which showed significant causal forcing from e-commerce to the aforementioned variables.

3.8.1 Australia

Figures 19 and 20 respectively show the results of simplex projection and S-map forecasting methods used to ascertain the existence of complex nonlinear behaviour in the underlying process. As shown in Figure 19, the best prediction skill is equal to or above 0.74 for all variables, with the dynamics of the data best unfolded when the lagged dimension E is between 6 to 8. A good univariate predictability indicates the data come from a system that exhibits a dynamic behaviour. The S-map procedure (Figure 20) also shows Australian data exhibits state-dependent behaviour as the θ that maximizes the univariate prediction skill (ρ) is greater than zero for all of them.

Figure 19: Univariate simplex forecast for Australian e-commerce and energy use variables

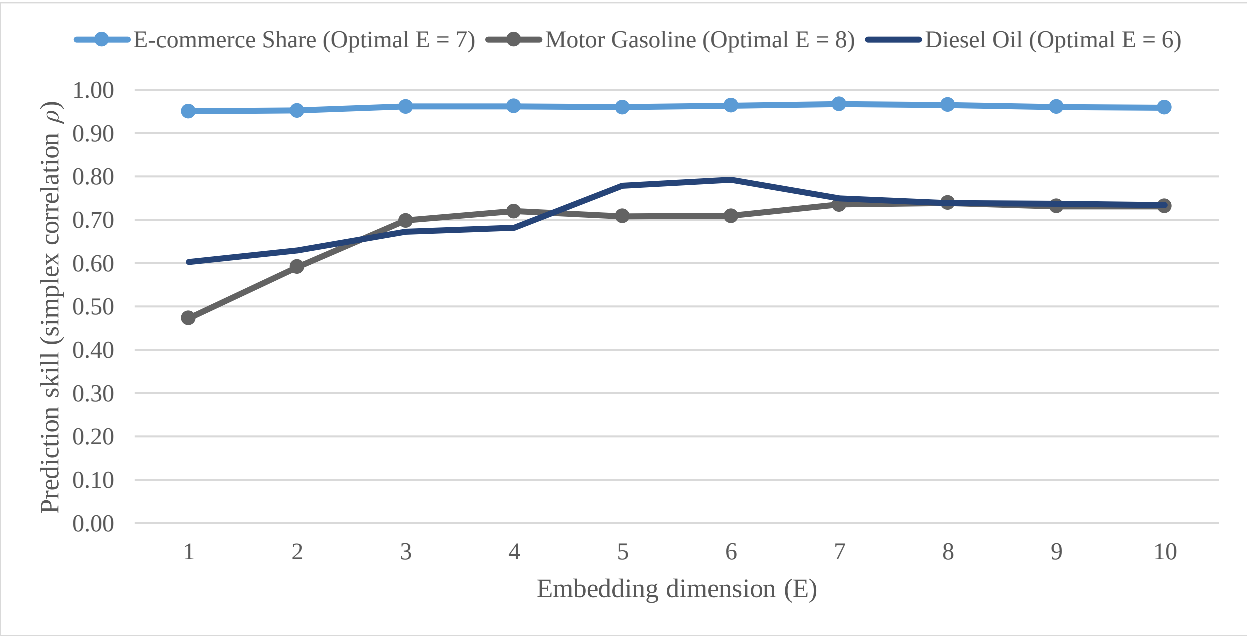


Figure 20: Univariate S-map forecast for Australian e-commerce and energy use variables

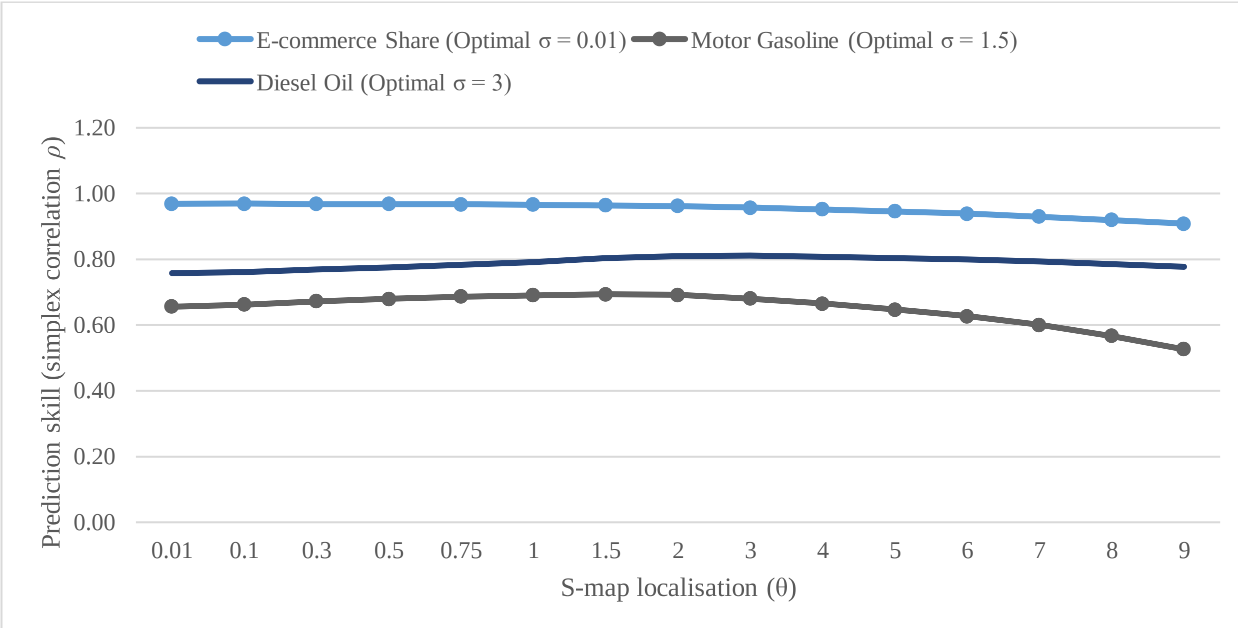
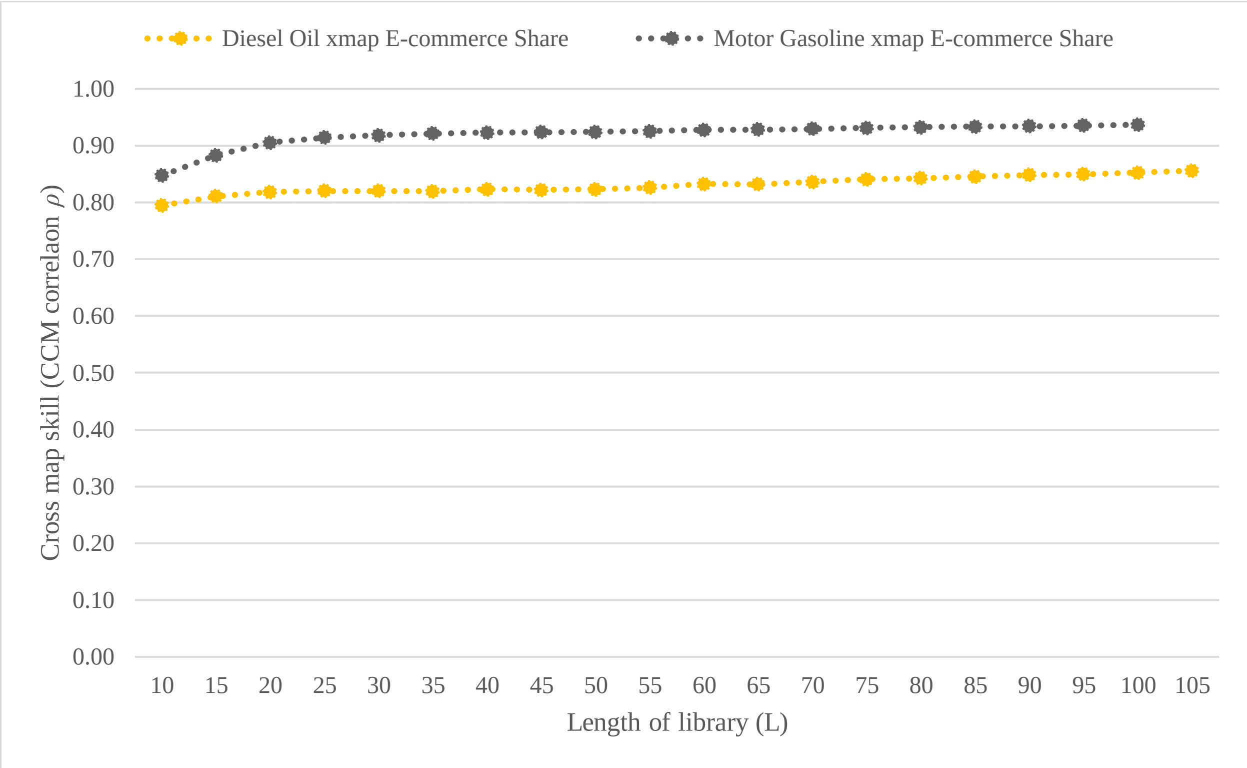


Figure 21 shows the results of the CCM causality test for the Australian data, i.e., the Pearson correlation of cross-mapped and observed values over the length of the time series (library size L). The cross-map skill for the Australian gasoline and diesel oil consumption improves and converges to almost unity as larger library sizes are utilized, confirming causal forcing from e-commerce to motor gasoline and diesel oil consumption for Australia.

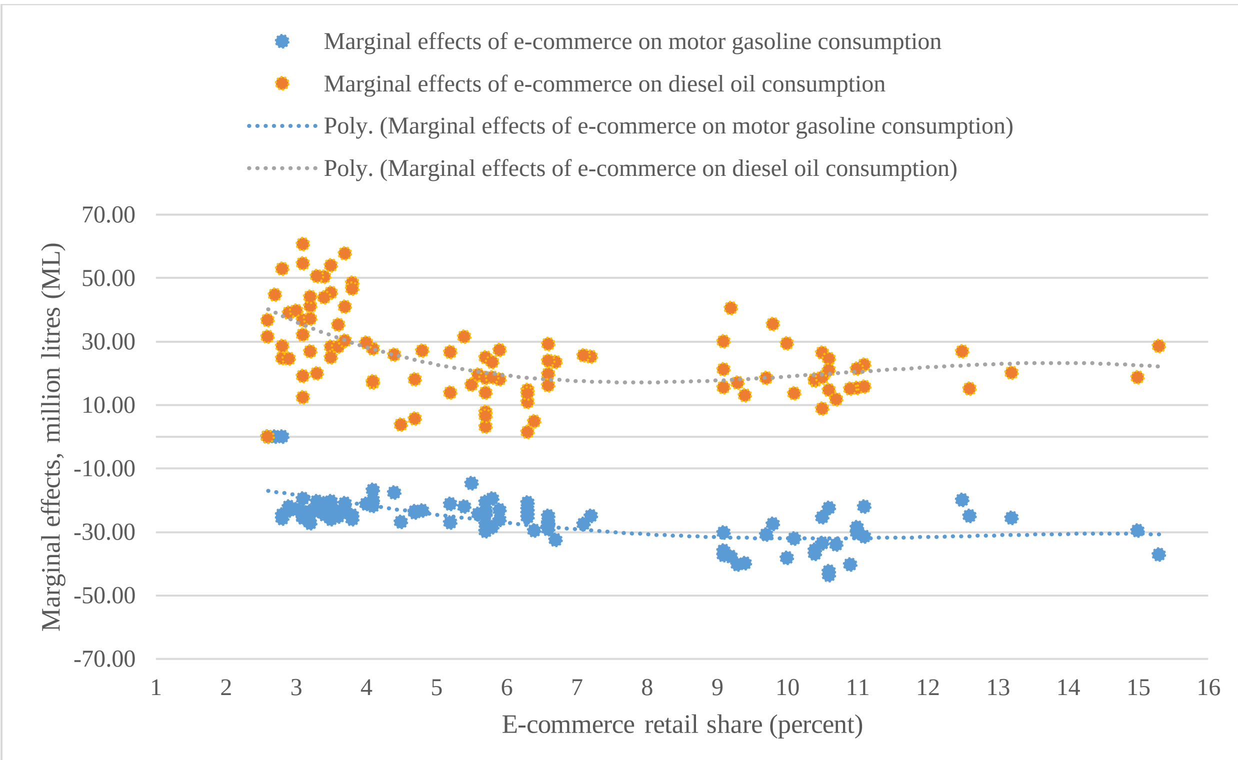
Figure 21: Correlation of cross-mapped versus observed value for Australian energy use variables



Given that causal forcing is established for the Australian data, the next step is to estimate the state-dependent marginal effects (Δ *energy use* /Δ *e-commerce share*) using the multivariate S-map method. Unlike the univariate S-map procedure that was used to identify nonlinear behaviour, the multivariate S-map includes e-commerce share as an additional explanatory variable in the lagged coordinate embeddings of the influenced variables (gasoline and distillate fuel oil consumption). State-dependent marginal effects are then estimated at the optimal E and θ parameters of the influenced variables.

Figure 22 shows a scatterplot of the marginal effects of e-commerce on gasoline and diesel oil consumption at different states of e-commerce penetration levels, fitted with a polynomial curve of order 4. Similar to the Canadian data, marginal effects for Australian gasoline consumption are largely negative and show relatively weak state dependence. However, a striking clustering emerges as the share of e-commerce crosses the 8 percent point: the average impact for the states of e-commerce greater than 8 percent (-33 ML) is higher in absolute terms than the average impact for the states of e-commerce less than 8 percent (-27 ML). It is possible that the COVID-19 pandemic may be confounding the results as the states of e-commerce greater than 8 percent coincide with the pandemic period.

Figure 22: Marginal effects of e-commerce on Australian fuel use at different e-commerce states



For diesel, unlike Canada where the impacts were negative, the results for Australia show positive state-dependent effects of e-commerce penetration on diesel consumption. This is theoretically expected for when conventional trade is replaced with e-commerce, the mode of transport changes from personal cars to freight trucks, increasing consumption of diesel oil. Over the 2013-2022 period, Australian diesel fuel consumption has, on average, increased by 26 million litres for every additional percentage point increase in retail e-commerce sales (Table 10). In relative terms, this increase represents an average effect of +1.1%.

Table 10: Mean marginal effects of e-commerce share on fuel consumption for Australia

	2013-2022		2020-2022	
Marginal effect of e-commerce on	Mean (ML)	Relative change	Mean (ML)	Relative change
Motor gasoline	(27)	-1.9%	(33)	-2.6%
Diesel oil	26	1.1%	21	0.8%

3.8.2 Taiwan

Unfortunately for Taiwan, data on monthly motor gasoline consumption was not available. However, the e-commerce retail share and diesel consumption pairings provided more datapoints (n=153) than Canada and Australia. The availability of Taiwanese diesel data allows us to further explore the conflicting state-dependent effects of e-commerce penetration on diesel consumption for Canada and Australia (negative for Canada, positive for Australia).

Similar to the Australian data, the dynamics of the Taiwanese data are best unfolded when the lagged dimension E is between 6 to 10, with the nonlinear localisation parameter (θ) exactly the same as in the Australian data (0.01 for e-commerce share and 3 for the diesel variable). Figure 23 shows the results of the CCM causality test for the Taiwanese data, and as shown, the cross-map skill between e-commerce retail share and diesel oil consumption improves and converges to a positive value as larger library sizes are utilized; confirming causal forcing from e-commerce to diesel oil consumption for Taiwan.

Figure 23: Correlation of cross-mapped versus observed value for Taiwanese energy use variables

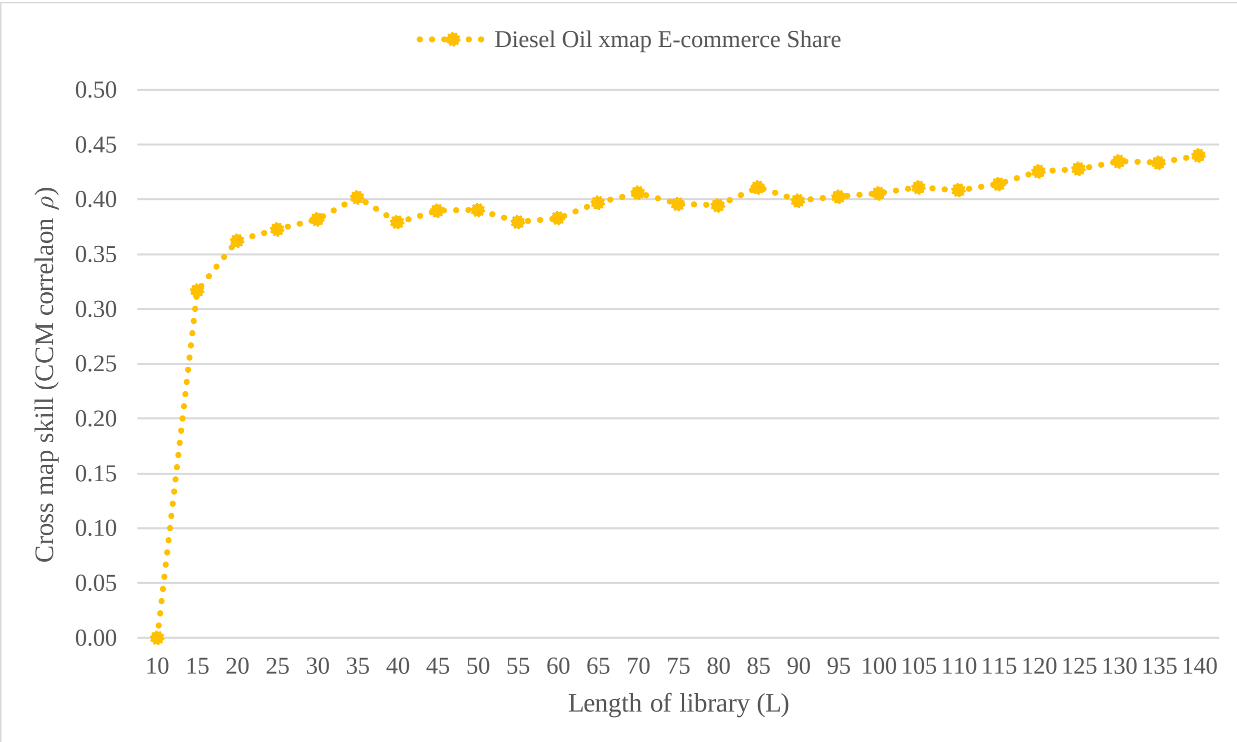


Figure 24 shows a scatterplot of the marginal effects of e-commerce on diesel oil consumption at different states of e-commerce penetration levels, fitted with a polynomial curve of order 4. Similar to the Australian data, marginal effects for Taiwanese diesel consumption are positive but show a relatively weaker state dependence than the Australian data. Over the 2010-2022 period, Taiwan diesel fuel consumption has, on average, increased by 21 million litres for every additional percentage point increase in retail e-commerce sales (Table 11). In relative terms, this increase represents an average effect of +4.5%, much higher than the Australian impact.

The reason for the higher impact is unclear to us, but it is possible that the Asian economy may have had higher predisposition for conventional personal shopping to begin with, which were replaced by freight delivery as e-commerce gained traction. The positive impacts for both Australia and Taiwan confirm the theoretical expectation that e-commerce tends to increase freight transport and hence diesel consumption. It also reaffirms our suspicion that the Canadian data may be confounded by diesel used in railroad locomotives, farm machinery, space heating and electric power generation that are included in the distillate fuel composite.

Figure 24: Marginal effects of e-commerce on Taiwan fuel use at different e-commerce states

Table11: Mean marginal effects of e-commerce share on fuel consumption for Taiwan

	2010-2022		**2020-22**	
Marginal effect of e-commerce on	Mean (ML)	Relative change	Mean (ML)	Relative change
Diesel Oil	21	4.5%	22	4.5%

3.9 Discussion and Conclusion

This study used the nonparametric EDM approach to investigate the impacts of increased e-commerce penetration on Canadian natural gas, motor gasoline and distillate fuel oil consumption. This approach overcomes the impracticality of specifying explicit equations for the analyzed economic data, given that the underlying e-commerce-energy-environment system may be complex, chaotic and scale-dependent. EDM analysis is centered on Takens' (1981) proof that the underlying dynamics of a complex system can be recovered just from the lagged coordinates of a single time series that is part of the system. Given the limited application of this procedure in social sciences, and particularly in e-commerce research, this study augments the existing literature.

The analysis showed that e-commerce did not influence Canadian residential, commercial, and industrial natural gas consumption over the 2016-2021 period. On the contrary, a causality test confirmed causal forcing from e-commerce to Canadian motor gasoline and distillate fuel consumption for the 2019-2021 period where monthly consumption data was available. On average, Canadian motor gasoline and distillate fuel consumption decreased by -1.0% and -2.3% respectively for every additional percentage point increase in retail e-commerce sales. The estimated result for the motor gasoline consumption is plausible, given that consumers reduce personal driving as they change their shopping behaviour more toward home delivery.

However, it is surprising to see a negative impact of e-commerce on distillate fuel oil consumption. As expected, when conventional trade is replaced with e-commerce, the mode of transport changes from passenger transport to freight transport, increasing consumption of distillate fuel oil. In addition, since shoppers tend to purchase from several online channels, e-commerce can potentially lead to many small and inefficient deliveries and product returns, which can increase the number and travel intensity of vehicles using diesel engines. One possible factor that confounds the results for Canadian distillate fuel oil is that the variable includes not only diesel used in on-road diesel engines, but also fuel used in railroad locomotives, farm machinery, space heating and electric power generation. The expected increase in on-road diesel consumption as a result of increased retail e-commerce sales may be offset by decreases in off-road use.

The direction of the impact the current analysis compares to Dost and Maier (2017) who found a small decrease (-0.23% in 2015) in U.S. transportation energy consumption for every one percentage point increase in e-commerce share. However, unlike the current study, the transportation energy consumption variable in Dost and Maier (2017) includes aggregate transportation energy use. In addition, analysis using the Australian data shows marginal effects for gasoline consumption, like Canada, are largely negative and shows a relatively weak state dependence. However, unlike Canada where the impacts on diesel were negative, the results for Australia and Taiwan show positive state-dependent effects of e-commerce on diesel use, a plausible outcome as the activity changes from passenger travel to freight transport with increased e-commerce penetration. Table 12 summarizes the analytical results for the three countries covered by this study. One important limitation of the current analysis is the unavailability of longer time series data for the variables investigated, especially for Canada, potentially affecting the prediction skill of the EDM procedures applied. The analysis could be augmented by collecting and utilizing primary data directly from firms through questionnaires and surveys to get a better sense of e-commerce penetration and link it with national and regional statistics on energy consumption. Subsequent research could cross-validate the empirical model by obtaining data from different countries to provide more insightful findings.

Table 12: Summary of the impact of E-commerce on energy consumption

	Diesel	Gasoline
Canada	−	−
Australia	+	−
Taiwan	+	N/A

Chapter Four

Summing it up: Research Implications, Recommendations And Future Research

4.1 Introduction

Online shopping has evolved into a mainstream business model over the last two decades, thanks to the development of information communication technology (ICT) infrastructure, the availability of broadband and the establishment of legal frameworks for consumer protection (Mangiaracina et al. 2015). Most recently, the Coronavirus pandemic has put alternative business systems into question, reinvigorating the rate at which e-commerce is penetrating national and global marketplaces. In today's post-pandemic world, not having some form of e-commerce platform represents a looming existential threat for most businesses.

In Chapter One of this thesis, we conducted a systematic review that provided a comprehensive understanding of the net environmental impacts of e-commerce over traditional retail. We found that e-commerce generally leads to better environmental outcomes than traditional retail, except at the packaging phase where it fares badly environmentally, likely due to the vast number of small orders shipped individually and the use of corrugated cardboard boxes. In Chapter Two, we conducted a meta-analysis to investigate Chapter One results further to overcome the fact that they were based on a simple univariate analysis of the reported differences in e-commerce vs traditional retail impacts from the reviewed studies.

The meta-analysis which estimated several successive regression analyses that controlled for the different study characteristics revealed two results. First, it confirmed the results of our systematic literature review that e-commerce packaging is an environmentally damaging activity. Secondly, on a life-cycle basis, switching from traditional retail to e-commerce does not seem to have any statistically significant impact on the environment. This suggests that the benefits from other stages of the e-commerce supply chain (production, transportation, and warehousing) outweigh the incremental environmental damages from the packaging phase.

In Chapter 3, we applied the nonparametric EDM approach to time series macroeconomic data to draw conclusions on the impact of increased e-commerce penetration on energy consumption. This approach helped us overcome the impracticality of specifying explicit equations for the analyzed economic data, given that the underlying e-commerce-energy-environment systems may be complex, chaotic, and scale-dependent. This analysis confirmed causal forcing from e-commerce to motor gasoline and diesel fuel consumption for Canada, Australia, and Taiwan; with e-commerce impact being negative for gasoline use and generally positive for diesel use (except for Canada). These results are plausible given that consumers reduce personal driving as they change their shopping behaviour more toward home delivery (which increases diesel consumption). Nonetheless, the overall effect on total gasoline and diesel consumption will depend on the fleet mix and the level of transport electrification in a country.

Taken together, these analyses reveal two important results. First, the advancement of e-commerce does not necessarily lead to negative environmental outcomes. This however does not mean that e-commerce is always comparatively better environmentally as the outcome will likely depend on the kind of energy material utilized. For instance, Imran et al. (2023), using thirty years of data from five developed Asian nations, showed that while carbon emissions decrease initially at the advent of e-commerce, emissions can increase as large-scale infrastructure supporting online trade is deployed. This is particularly the case for cloud-based data centers, e-payment systems, and blockchains, with the latter increasing the demand on cryptocurrencies and consumption of vast amount of energy. Thus, the negative impact of e-commerce on the environment may likely increase. According to Jeba et al. (2021), there is need to review the technology used in cloud computing and implement green clouds and algorithms that are more energy efficient and environment friendly. Amid expanding e-commerce trade, this result presents an opportunity for governments and enterprises to prioritize research and development of eco-friendly ICT in order to minimize the damage to the environment.

The second striking result from the current research is that e-commerce packaging, when considered in isolation, is not environmentally-friendly, largely due to the vast number of small orders shipped individually and the use of corrugated cardboard boxes. In addition, products ordered via e-commerce platforms not only require external packaging, “but also fillers such as inflatable packaging films, bubble pads, air column buffer bags, and sealing tapes” (Wang et al. 2022, p. 11). The production of these materials is usually energy-intensive and many of them end up as trash in the natural ecosystem after use. To address this issue and therefore balance the economic and environmental outcomes of e-commerce, firms and policy makers should rethink the whole approach to designing, producing, and using packaging materials in order to improve the environmental performance of the entire system.

4.2 Research Implications and Recommendations

Today’s policy makers and leaders of private enterprises are endeavouring to deal with a major climate crisis that threatens the liveability of our planet. Given how factors such as the increased internet connectivity, the deployment of large-scale ICT infrastructure and global shocks (such as pandemics) are contributing to the pace of economic digitalization, we put forward recommendations based on the two main findings from the current research. Ensuring sustainable e-commerce pathway for the future requires efforts from multiple stakeholders such as civil society organizations, private enterprises, and governments, and we therefore recognize the need to provide targeted recommendations. Ultimately, however, the success in achieving a sustainable e-commerce outcome will depend on collaboration and co-ordinated governance from all agents.

4.3 Civil Society Organizations

Civil societies are voluntary citizens' groups organized around specific issues that are of concern to the society they represent. While they may lobby governments and private sector organization on environmental protection, it is vital that they recognize consumers are the ultimate polluters as firms increase production of goods in response to higher demand from consumers. In addition, consumers tend to place multiple small orders and these products are overpackaged because consumers want them delivered without damage. It is therefore important for consumers and consumer groups to recognize this and begin their charity work at home.

In order to drive this notion home, we recommend civil society organizations to focus on two things. First, they should educate consumers and raise public awareness around environmental protection and the risks of climate change. A considerable portion of the global population today are either in denial of or uninformed about the looming climate crisis and the importance of sustainable environmental stewardship. The imperative task here is to provide basic scientific education on climate and environmental issues and debunk conspiracy theories, before engaging in dialogues about the effect of human consumption patterns on the environment. The idea is to first cement a consistent and common knowledge across the largest swath of the global population that the climate is in fact changing, regardless of the cause.

The second recommendation for civil society organizations follows from the first one. Once basic scientific climate knowledge is imparted, civil societies should raise awareness on the environmental footprint of consumers' consumption patterns. Previous studies have shown that increased public environmental awareness could induce behavioral changes among consumers, whether it is bundling items together in one order to reduce the number of online transactions

(Loon et al. 2015, Xie et al. 2021) or choosing to buy products locally to minimize the need for excess packaging (Wang et al. 2022). Other studies have even shown that public environmental awareness positively influences consumer preferences for combined packaging solutions (Loon et al. 2015, Chueamuangphan et al. 2019). Civil societies, therefore, need to capitalize on this information and get across the message that markets generally tend to respond positively to consumer signals and that environmental protection initiatives will be successful if they have strong public support.

One approach civil society organizations can utilize to increase public awareness and influence how goods are produced is through the use of ICTs. ICTs, particularly digital media, allow consumers and other actors to get information on the environmental footprint of companies, brands or products and hence support them to make informed decisions when buying merchandise. This in turn drives private firms to respond to market signals and alter their operations in order to become more environmentally friendly. Civil societies can also effectively utilize digital media to shed light on the environmental actions of the governments of the day and hold them accountable through greater public awareness. As more and more people become environmentally conscious, greater transparency on the actions of firms and governments is achieved.

4.4 Firms

Similar to consumers, private enterprises have an equally important role in minimizing the environmental impacts of contemporary digitalization of the global economy. To begin with, we recommend businesses to incorporate environmental and social responsibility into their business models. Such decision should be viewed not just from a moral lens, but from a strategic economic standpoint that is essential for long-term corporate survivability. Using a large sample of companies operating in the European financial markets, Ionaşcu et al. (2022) find that firms that are environmentally and socially responsible are rewarded with more capital by investors. Equally, it has been shown that consumers' attachment to a certain product is positively influenced by the producer's action on environmental protection (Zhao et al. 2021).

In the context of this study, firms should capitalize on our finding that, on a life-cycle basis, switching from traditional retail to e-commerce does not seem to be environmentally damaging. They should continue to scrutinize the environmental impacts of their business decisions, expand their corporate social responsibility divisions, and invest in sustainable business processes. Clearly, this research identified e-commerce packaging as an environmentally damaging process, we therefore recommend private enterprises to focus on developing eco-friendly packaging solutions. Research has shown that consumers display strong preference for enterprises that have established an efficient package recycling systems (Xie et al. 2021). Similarly, consumers' trust, attachment to and perception of brand value is strongly influenced by an enterprise's greening of its packaging process (Zhao et al. 2021).

We also recommend private enterprises to invest in the development of sustainable e-commerce infrastructure in order to improve the long-term environmental performance of e-business platforms. This is not just in relation to packaging (which was shown to be environmentally damaging) but to the entire value chain, from manufacturing the technology that enables e-commerce to the production and final distribution of the consumer products traded online. For instance, a considerable share of ecological degradation associated with e-commerce comes from the production, use and disposal of ICT infrastructure and devices (Berkhout & Hertin, 2004). ICT hardware is composed of toxic materials which normally have a very short life span, consume a substantial amount of energy and produce a lot of electronic waste. There is, therefore, an opportunity for firms to increase investment in research and development in order to produce long-lasting devices that are sourced from renewable materials and are more energy efficient.

Innovative solutions should also extend to other aspects of business enterprises to include the use of renewable sources for power, the development of biodegradable materials for packaging, as well as revolutionizing packaging designs to optimize space and reduce waste (Sílvia et al. 2020). The latter two are critically important in light of the findings from this research and may even have the added economic advantage of cutting an enterprise's packaging costs. In addition, it has been argued that innovative packaging would minimize damage of goods during delivery, hence increasing customer satisfaction (Williams et al. 2008), while allowing end-users to easily disassemble and recycle the packaging materials (Duan et al. 2019).

There are indications that large e-commerce firms are taking actions. For example, Amazon saves a lot of storage costs by integrating inventories in distribution centers and warehouses. As a result, there is no need to keep a high level of inventory in physical retail stores. Amazon has different processing procedures and equipment when dealing with various product groups. Those products which are easily classified and transported are stored in highly automated equipment while those irregularly shaped products are handled by equipment of low-level automation. When dealing with inter-city transportation, Amazon sets some injection points, i.e. transportation hubs (Cronin, 2014), which are in districts where customers are highly concentrated to save on delivery costs. In addition, Amazon has zoning delivery areas, where each truck or van is designated in a specific location, hence consuming less energy. E-commerce companies can also start investing in electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) for delivery of parcels as the rise in e-commerce has increased last mile parcel deliveries, in turn affecting the sustainability of transportation.

Finally, we recommend private enterprises to engage in green marketing and raise environmental awareness among their consumer bases. Investopedia[5] defines green marketing as the "practice of developing and advertising products based on their real or perceived environmental sustainability" (Investopedia 2023). This way, firms can promote and recommend eco-friendly products to online shoppers. Research has shown that consumers who are environmentally conscious tend to purchase eco-friendly products (Lu et al. 2020) and this can in fact promote the transition to a green e-commerce future (Chueamuangphan et al. 2019). Similarly, green marketing may increase the demand for products with eco-friendly packaging among consumers, thereby pressuring businesses to invest in sustainable packaging (FoodBev Media 2018)[6].

4.5 Government

Governments can play a much greater role in promoting a sustainable e-commerce future, whether it is through legislative power, creating economic incentives, promoting environmental awareness among actors, or investing in research and development. Governments can also play a crucial co-ordination role, where on one hand, they oversee and regulate the actions of private firms, and on the other, promote eco-friendly behaviors among consumers. In fact, Xie et al. (2021) found that consumers' preference for sustainably produced products is positively influenced by government policies and that the state plays a crucial role in establishing an effective recycling system.

Given the above, we recommend governments to optimally utilize the right policy levers to achieve better environmental outcomes. One way to accomplish this is through market-based solutions such as taxes and subsidies. It is a well-known economic fact that competitive markets -

[5] https://www.investopedia.com/terms/g/green-marketing.asp
[6] https://www.foodbev.com/news/new-research-reveals-consumer-demand-for-green-packaging/

while efficient in pricing and allocating private resources - fail when it comes to the provision of socially optimal levels of public goods, including ambient air quality. Through market-based mechanisms, governments can make e-commerce markets work to the service of the environment by, for instance, taxing emissions and waste and subsidizing ecologically beneficial goods.

Environmental levies on ecologically hazardous products allow companies to internalize the levies in their production decisions and incentivize them to pursue technological innovations in order to avoid paying tax penalties. A good example of such a policy as it relates to packaging is the United Kingdom's Plastic Packaging Tax which came into force in April 2022. This policy imposed a tax of £200 per tonne (which increased to £210.82/tonne from April 2023) on plastic packaging with less than 30 percent recycled plastic, regardless of whether the plastic was produced or imported into the United Kingdom[7]. Subsidies can also play an important role in bringing green technologies, products, and practices to market. Wang et al. (2022) argue that, when it comes to eco-friendly packaging solutions, private enterprises are not motivated to innovate actively and therefore governments should subsidize and encourage producers to invest in green and recyclable packaging materials.

We also recommend governments to explore other regulatory levers, where market-based mechanisms do not work or are not the best policy solutions to control the environmental effects of e-commerce. For instance, governments may enact legislations that strictly require businesses to utilize renewable or recyclable resources in the production of packaging materials or other consumer goods. Kenya, for example, enacted the world's strictest legislation on single-use plastic bags in 2017, making the manufacture, sale, and distribution of plastic bags illegal and imposing a fine of $40,000 or a prison sentence of up to four years on anyone found doing so. This ban has

[7] https://www.gov.uk/guidance/check-if-you-need-to-register-for-plastic-packaging-tax

generally been hailed a success, despite some implementation challenges[8] (BBC, 2019). Establishing mandatory recycling programs and improving garbage classification and disposal have also shown promising results, with Germany achieving success in reducing excessive packaging with such regulations (Wang et al. 2022).

Since environmental goods such as clean ambient air are public goods, we recommend governments to take the lead when it comes to investments in research and development. As it relates to product packaging, which this research has found to be ecologically damaging, this can range from investments in renewable energy sources to the development of biodegradable e-commerce packaging materials and the deployment of state-of-the-art recycling infrastructure. In other words, investments in research and development should cover the complete value chain of e-commerce product packaging, from material research to the final recycling or reuse. We recommend governments not only to invest in research and development, but to make such research and related innovative solutions accessible to private enterprises, and to fund the deployment of pilot programs independently or through public-private partnerships. In addition, governments should play a coordination role, where they connect public and private ventures in green packaging products and infrastructure to achieve synergies.

Finally, we recognize governments are in a better position to encourage eco-friendly behaviors and raise environmental awareness among consumers and firms. This recognition stems from the fact that governments possess a large pool of public resources, be it financial or human resources. Unlike resource-constrained civil society organizations or profit-oriented private enterprises, governments can unleash large-scale campaigns to educate the public on climate and environmental issues, debunk conspiracy theories and raise awareness on the environmental

[8] https://www.bbc.com/news/world-africa-49421885

footprint of e-commerce supply chain, especially when it comes to packaging material production, use and disposal.

4.6 Conclusion and Future Research

This chapter amalgamates the analytical results from the first three chapters of the current study on the environmental impacts of e-commerce, and provides targeted recommendations to consumers, private enterprises and governments. The study reveals two important conclusions. First, the advancement of e-commerce does not necessarily lead to negative environmental outcomes. This however does not mean that e-commerce is always comparatively environmentally better as the outcome will likely depend on business processes and the kind of energy material utilized. Secondly, e-commerce packaging, when considered in isolation, is environmentally damaging, principally due to the vast number of small orders and the use of corrugated cardboard boxes. The production and transportation of these packaging materials is usually energy-intensive and many of them end up as trash in the natural ecosystem after use.

Given these results, we first recommend civil society organizations representing the public to educate consumers on environmental protection and the risks of climate change. Once this basic scientific climate knowledge is conveyed, civil societies can then raise awareness on how the behavior and actions of consumers are negatively affecting our planet. Increased environmental consciousness could induce behavioral changes among consumers, whether it is choosing to buy products locally to minimize the need for excess packaging or bundling items together to reduce the number of online transactions.

For firms, in addition to prioritizing environmental and social responsibility, developing eco-friendly packaging solutions, and engaging in green marketing, we recommend them to invest in the development of sustainable e-commerce infrastructure to improve the long-term environmental performance of e-business platforms. Amid expanding e-commerce trade, and as a considerable share of ecological degradation associated with e-commerce comes from the production, use and disposal of ICT infrastructure, there is an opportunity for firms to increase investment in research and development to produce long-lasting devices that are sourced from renewable materials and are more energy efficient. Encouraging firms to cooperate in research and development (R&D) to introduce more eco-friendly products can have significant benefits for both the environment and the companies involved. Benefits of cooperation in R&D include sharing resources and expertise, reducing R&D costs, accelerating innovation, accessing new market and improving sustainable performance of companies.

For governments, the research recommends relevant state authorities to utilize the right policy levers to achieve better environmental outcomes, preferably through market-based solutions but also exploring other regulatory levers where market-based mechanisms are not suitable. We recommend governments not only to spearhead in research and development investments, but to make such research and related innovative solutions accessible to private enterprises, and to fund the deployment of pilot programs. Finally, given their large pool of financial and non-financial resources, we recommend governments to unleash large-scale campaigns to educate the public on climate and environmental issues, debunk conspiracy theories and raise awareness on the environmental footprint of e-commerce supply chain, especially as it relates to packaging material production and use.

In light of this analysis, future research should look into effective public and private measures that can be deployed to improve the environmental outcomes of e-commerce, especially around product packaging. For example, one can look into how market-based and other regulatory policy levers fare when it comes to reducing e-commerce pollution and where a combination of these policies is the better strategy. Future research could also consider similar analysis for different sectors of the economy or expand the current analysis to include more countries or regions, to see if the conclusions continue to hold. Finally, one might examine how green marketing, where firms promote and recommend eco-friendly products to online shoppers, can be utilized to increase environmental sustainability of e-commerce.

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Table 20-10-0072-01 Retail e-commerce sales (x 1,000)http://opetchey.github.io/RREEBES/Sugihara_and_May_1990_Nature/Simplex_projection_walkthrough.html

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Appendices

Appendix 1: Characteristics of the full-text studies assessed for eligibility

No.	Author (year)	Year	Title	Journal	Country	Research Method
1	Abukhader, S. M., & Jönson, G.	2003	The environmental implications of electronic commerce.	Management of Environmental Quality	Sweden	Literature review
2	Abukhader, S. M., & Jonson, G.	2004	E-commerce and the environment: A gateway to the renewal of greening supply chains. International Journal of Technology Management, 28(2), 274-288.	Int. J. Technology Management	Sweden	Analytical
3	Allen, J., Piecyk, M., Piotrowska, M., McLeod, F., Cherrett, T., Ghali, K., ... & Wise, S.	2018	Understanding the impact of e-commerce on last-mile light goods vehicle activity in urban areas.	Transport and Environment	United Kingdom	Case study
4	Berkhout, F., & Hertin, J.	2004	De-materialisingandre-materialising:digital technologies and the environment	Futures	United Kingdom	Literature review
5	Borggren, C., Moberg, Å., & Finnveden, G.	2011	Books from an environmental perspective—Part 1: environmental impacts of paper books sold in traditional and internet bookshops.	The International Journal of Life Cycle Assessment	Sweden	Life cycle assessment
6	Cao, J., Xu, B., & Wang, J.	2019	Optimal Channel Choice of Firms with New and Remanufactured Products in the Contexts of E-Commerce and Carbon Tax Policy.	Sustainability	China	Game theory
7	Carrillo, J. E., Vakharia, A. J., & Wang, R.	2014	Environmental implications for online retailing.	European Journal of Operational Research	United States	Analytical
8	Caudill, R. J., Luo, Y., Wirojanagud, P., & Zhou, M.	2000	A lifecycle environmental study of the impact of e-commerce on electronic products.	IEEE International Symposium on Electronics and the Environment	United States	Life cycle assessment

9	Caulfield, B.	2009	Estimating the environmental benefits of ride-sharing: A case study of Dublin.	Transport and Environment	Ireland	Case study
10	Chen, W., & Yan, W.	2020	Impact of internet electronic commerce on SO2 pollution: evidence from China	Environmental Science and Pollution Research	China	Analytical
11	Chunfang, W., Ming, X., & Yanqiu, X.	2019	Research on Innovation and Application of Green Packaging Energy Saving Technology for E-commerce Logistics	Earth and Environmental Science	China	Literature review
12	Cullinane, S.	2009	From bricks to clicks: the impact of online retailing on transport and the environment.	Transport Reviews	United Kingdom	Empirical
13	Dost, F., & Maier, E.	2018	E-Commerce effects on energy consumption: A multi-year ecosystem-level assessment.	Journal of Industrial Ecology	Germany	Empirical
14	Edwards, J. B., McKinnon, A. C., & Cullinane, S. L.	2010	Comparative analysis of the carbon footprints of conventional and online retailing	International Journal of Physical Distribution & Logistics Management	United Kingdom	Analytical
15	Weiguo, F., Ming, X., Xiaobin, D., & Hejie, W.	2017	Considerable environmental impact of the rapid development of China's express delivery industry	Resources, Conservation & Recycling	China	Assessment
16	Fichter, K.	2002	E-commerce: Sorting out the environmental consequences.	Journal of Industrial Ecology	Germany	Life cycle assessment
17	Fuchs, C.	2008	The implications of new information and communication technologies for sustainability	Environment, Development and Sustainability	Austria	
18	Gay, R. H., Davis, R. A., Phillips, D. T., & Sui, D. Z.	2005	Modeling Paradigm for the Environmental Impacts of the Digital Economy	Organizational Computing and Electronic Commerce	United States	Simulation
19	Hiselius, L. W., Rosqvist, L. S., & Adell, E.	2015	Travel Behaviour of Online Shoppers in Sweden	Transport and Telecommunication Journal	Sweden	Survey
20	Jaller, M., & Pahwa, A.	2020	Evaluating the environmental impacts of online shopping: A behavioral and transportation approach	Transport and Environment	United States	Econometric
21	Jnr, B. A., Majid, M. A., & Romli, A.	2019	Green information technology adoption towards a sustainability policy agenda for government-based institutions.	Journal of Science and Technology Policy Management	Malaysia	Case study
23	Kikovska–Georgievska, S.	2013	E-commerce – Challenge for sustainable development of companies	Journal of Sustainable Development	Macedonia	Analytical

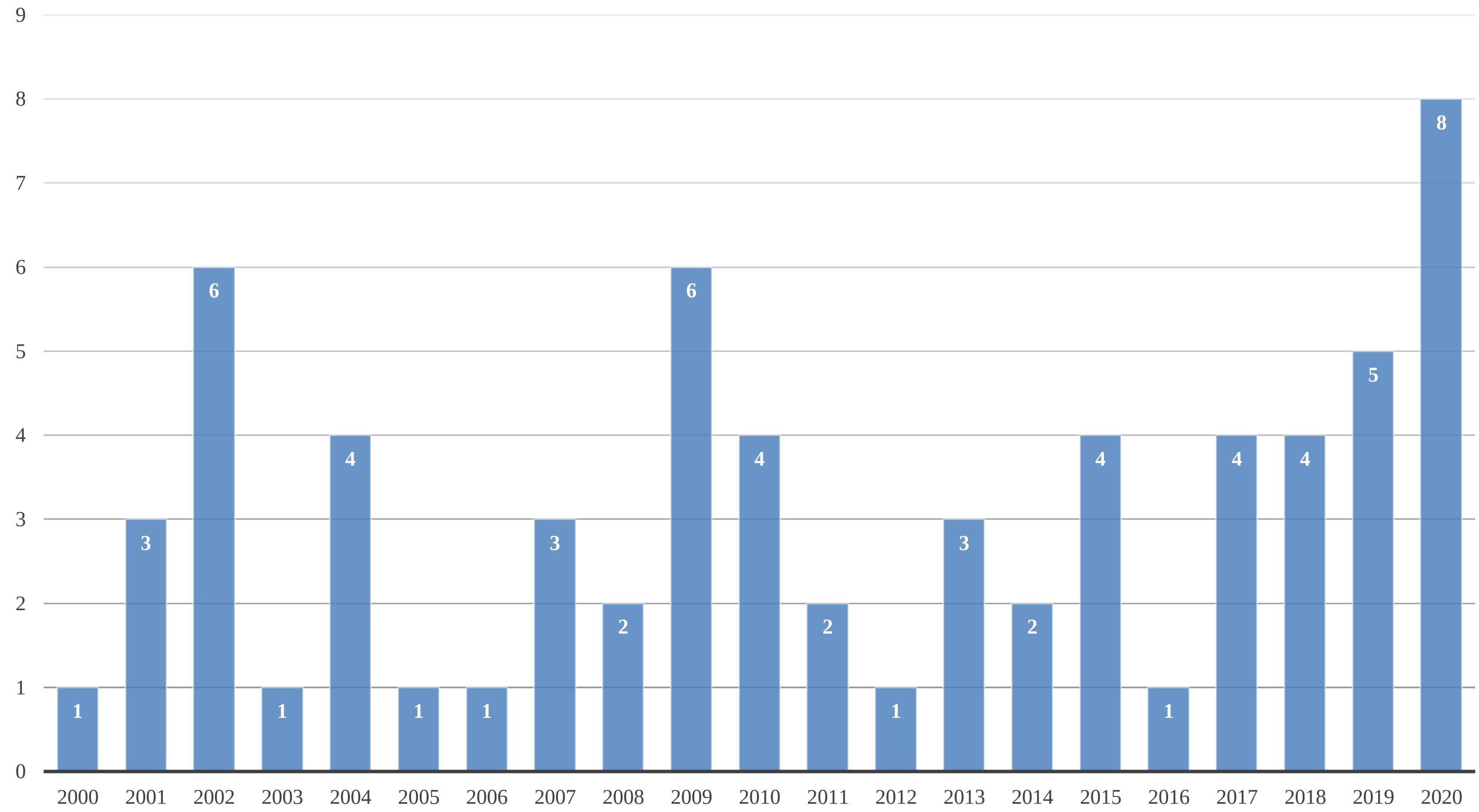
24	Koiwanit, J.	2018	Analysis of environmental impacts of drone delivery on an online shopping system.	Advances in Climate Change Research	Thailand	Life cycle assessment
25	Kostopoulos, V., & Andreopoulou, Z.	2018	E-Commerce and Renewable Energy Sources in Southern Greece	Journal of Regional & Socio-Economic *Issues*, *8*.	Greece	Analytical
26	Lalitha R., Usha S., Mohamed Ibrahim M., Mannoj M., Mukesh Kanna S.	2020	A novel E-business model for sustainable green environment by using crop stubble	Journal of Green Engineering	India	Framework
27	Loeser, F., Recker, J., Brocke, J. V., Molla, A., & Zarnekow, R.	2017	How IT executives create organizational benefits by translating environmental strategies into Green IS initiatives	Information Systems Journal	Germany	Survey
28	Lu, S., Yang, L., Liu, W., & Jia, L.	2020	User preference for electronic commerce overpackaging solutions	Implications for cleaner production. Journal of Cleaner Production	China	Analytical
29	Mangiaracina, R., Marchet, G., Perotti, S., & Tumino, A.	2015	A review of the environmental implications of B2C e-commerce: a logistics perspective	International Journal of Physical Distribution & Logistics Management	Italy	Literature review
30	Matthews, H. S., Williams, E., Tagami, T., & Hendrickson, C. T.	2002	Energy implications of online book retailing in the United States and Japan	Environmental Impact Assessment Review	United States	Life cycle assessment
31	Matthews, H. S., Hendrickson, C. T., & Soh, D.	2001	The net effect: Environmental implications of e-commerce and logistics.	Institute of Electrical and Electronics Engineers	United States	Analytical
32	Oláh, J., Kitukutha, N., Haddad, H., Pakurár, M., Máté, D., & Popp, J.	2019	Achieving Sustainable E-Commerce in Environmental, Social and Economic Dimensions by Taking Possible Trade-Offs	Sustainability	Hungary	Literature review
33	Tang, A. K., Lai, K. H., & Cheng, T. C. E.	2016	A multi-research-method approach to studying environmental sustainability in retail operations.	International Journal of Production Economics	Hong Kong	Quantitative and Qualitative

34	Scott Matthews, H., Hendrickson, C. T., & Soh, D. L.	2001	Environmental and economic effects of e-commerce: A case study of book publishing and retail logistics	Transportation Research	United States	Case study
35	McLeod, F., Cherrett, T., & Song, L.	2006	Transport impacts of local collection/delivery points	International Journal of Logistics	United Kingdom	Analytical
36	Mokhtarian, P. L.	2004	A conceptual analysis of the transportation impacts of B2C e-commerce	Transportation	United States	Conceptual
37	Pålsson, H., Finnsgård, C., & Wänström, C.	2013	Selection of Packaging Systems in Supply Chains from a Sustainability Perspective: The Case of Volvo	Packaging Technology & Science	Sweden	Case study
38	Pålsson, H., Pettersson, F., & Hiselius, L. W.	2017	Energy consumption in e-commerce versus conventional trade channels - Insights into packaging, the last mile, unsold products and product returns	Journal of Cleaner Production	Sweden	Literature review
39	Popescu, G. H.	2015	E-commerce effects on social sustainability	Economics Management and Financial Markets	Romania	Assimilates
40	Reijnders, L., & Hoogeveen, M. J.	2001	Energy effects associated with e-commerce: A case-study concerning online sales of personal computers in The Netherlands	Journal of Environmental Management	Netherlands	Case study
41	Rivera, M. B., Håkansson, C., Svenfelt, Å., & Finnveden, G.	2014	Including second order effects in environmental assessments of ICT	Environmental Modelling & Software	Sweden	Analytical
42	Rotem-Mindali, O.	2010	E-tail versus retail: The effects on shopping related travel empirical evidence from Israel	Transport Policy	Israel	Analytical
43	Rotem-Mindali, O., & Salomon, I.	2007	The impacts of E-retail on the choice of shopping trips and delivery: Some preliminary findings	Transportation Research	Israel	Conceptual
44	Siikavirta, H., Punakivi, M., Kärkkäinen, M., & Linnanen, L.	2002	Effects of E-Commerce on Greenhouse Gas Emissions A Case Study of Grocery Home Delivery in Finland	Journal of industrial ecology	Finland	Case study
45	Sivaraman, D., Pacca, S., Mueller, K., & Lin, J.	2007	Comparative Energy, Environmental, and Economic Analysis of Traditional and E-commerce DVD Rental Networks	Journal of Industrial Ecology	United States	Life cycle assessment

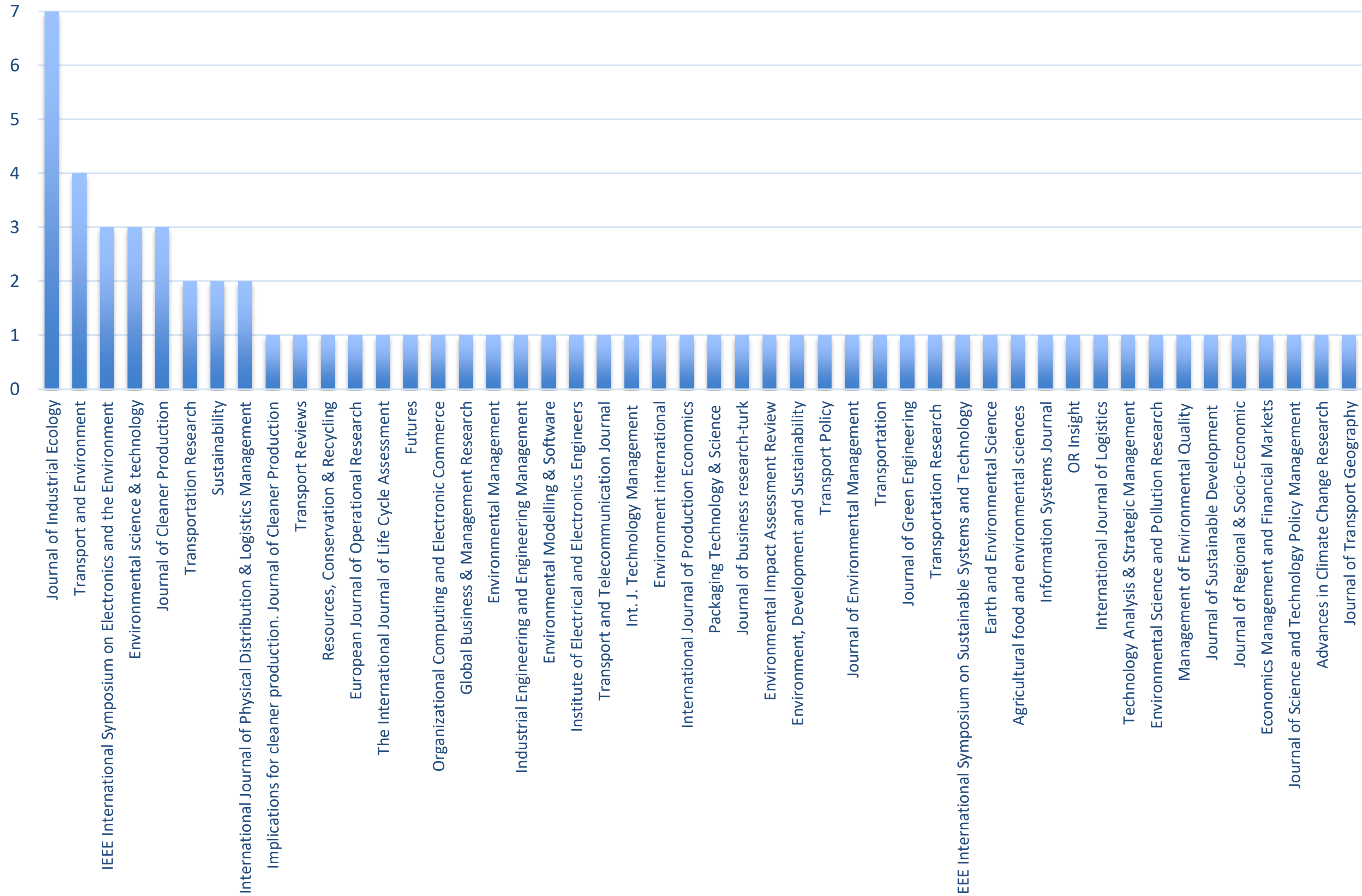
46	Song, L., Cherrett, T., & Guan, W.	2011	Implications of collection/delivery points for transport and logistics	OR Insight	United Kingdom	CDP
47	Sui, D. Z., & Rejeski, D. W.	2002	Environmental Impacts of the Emerging Digital Economy: The E-for-Environment E-Commerce?	Environmental Management	United States	Literature review
48	Tehrani, S. M., Karbassi, A. R., Ghoddosi, J., Monavvari, S. M., & Mirbagheri, S. A.	2009	Prediction of energy consumption and urban air pollution reduction in e-shopping adoption	Agricultural food and environmental sciences	Iran	Analytical
49	Van Loon, P., Deketele, L., Dewaele, J. McKinnon, A., & Rutherford, C.	2015	A comparative analysis of carbon emissions from online retailing of fast moving consumer goods	Journal of Cleaner Production	United Kingdom	Life cycle assessment
50	Velásquez, M., Ahmad, A. R., Bliemel, M., & Imam, M. H.	2010	Online vs. Offline Movie Rental: A Comparative Study of Carbon Footprints	Global Business & Management Research	Canada	Life cycle assessment
51	Weber, C. L., Hendrickson, C. T., Matthews, H. S., Nagengast, A., Nealer, R., & Jaramillo, P.	2009	Life Cycle Comparison of Traditional Retail and E-commerce Logistics for Electronic Products: A Case Study of buy.com	IEEE International Symposium on Sustainable Systems and Technology	United States	Case study
52	Weber, C. L., Koomey, J. G., & Matthews, H. S.	2010	The energy and climate change implications of different music delivery methods	Journal of Industrial Ecology	United States	Life cycle assessment
53	Weltevreden, J. W., & Rotem-Mindali, O.	2009	Mobility effects of b2c and c2c e-commerce in the Netherlands: a quantitative assessment	Journal of Transport Geography	Netherlands	Quantitative
54	Wiese, A., Toporowski, W., & Zielke, S.	2012	Transport-related CO2 effects of online and brick-and-mortar shopping: A comparison and sensitivity analysis of clothing retailing	Transport and Environment	Germany	Analytical
55	Williams, E., & Tagami, T.	2002	Energy Use in Sales and Distribution via E-Commerce and Conventional Retail	Journal of Industrial Ecology	Japan	Case study

56	Williams, E. D.	2002	Energy efficiency of b2c e-commerce in Japan	IEEE International Symposium on Electronics and the Environment	Japan	Life cycle assessment
57	Xu, M., Kim, J., Kahhat, R., & Allenby, B.	2008	Market Dynamics and Environmental Impacts of E-commerce: A Case Study on Book Retailing	IEEE International Symposium on Electronics and the Environment	United States	Case study
58	Xu, M., Allenby, B., Kim, J., & Kahhat, R.	2009	A dynamic agent-based analysis for the environmental impacts of conventional and novel book retailing	Environmental science & technology	United States	Analytical
59	Yi, L., & Thomas, H. R. (	2007	A review of research on the environmental impact of e-business and ICT	Environment international	United Kingdom	Literature review
60	Zhang, L., & Zhang, Y.	2013	A Comparative Study of Environmental Impacts of Two Delivery Systems in the Business-to-Customer Book Retail Sector	Journal of Industrial Ecology	China	Analytical
61	Adam, I. O., Alhassan, M. D., & Afriyie, Y.	2020	What drives global B2C E-commerce? An analysis of the effect of ICT access, human resource development and regulatory environment	Technology Analysis & Strategic Management	Ghana	Analytical
62	Çakilci, C., & Özturhoglu, Y.	2020	Analysis of Sustainable E-Logistics Activities with Analytic Hierarchy Process	Journal of Business Research	Turkey	Analytical
63	Cherrett, T. et. al	2017	Logistics impacts of student online shopping - evaluating delivery consolidation to halls of residence.	Transportation Research	United Kingdom	Questionnaire
64	Escursell, S., Llorach, P., & Roncero, M. B.	2020	Sustainability in E-commerce packaging: A review	Journal of cleaner production	Spain	Literature review
65	Shahmohammadi et.al	2020	Comparative Greenhouse Gas Foot printing of Online versus Traditional Shopping for Fast-Moving Consumer Goods: A Stochastic Approach	Environmental science & technology	Netherlands	Stochastic Approach
66	Toffel, M. W., & Horvath, A.	2004	Environmental Implications of Wireless Technologies: News Delivery and Business Meetings	Environmental Science & Technology	United States	Literature review
67	Velazquez, R., & Chankov, S. M.	2019	Environmental Impact of Last Mile Deliveries and Returns in Fashion E-Commerce: A Cross-Case Analysis of Six Retailers	Industrial Engineering and Engineering Management	Germany	Life cycle assessment

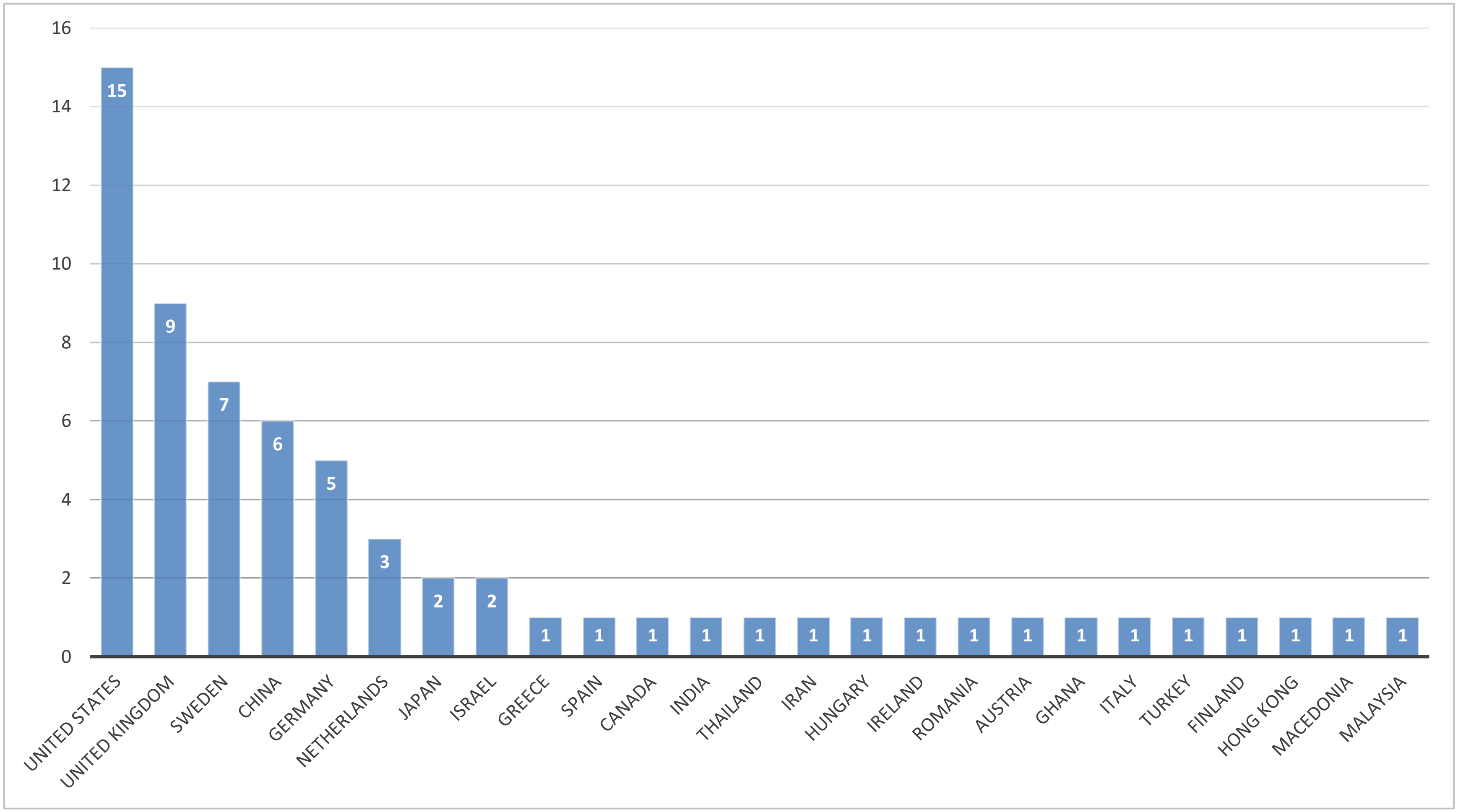
Appendix 2: Distribution of publication years for the full-text studies



Appendix 3:Distribution of journals for the full-text studies



Appendix 4: Distribution of first-author country for the full-text studies



Appendix 5: Comparative data retrieved from the studies

Study No.	Logistical Activity	E-commerce type	Environmental Indicator	Product	Unit	Geography	E-commerce	Traditional	Percent Impact of E-commerce
5	Life-Cycle	B-2-C	CO2-eq	Paper book	KG	Suburban	1.1	1.3	-15.4%
5	Life-Cycle	B-2-C	Energy Use	Paper book	MJ eq	Suburban	40	56	-28.6%
5	Life-Cycle	B-2-C	SO2 eq	Paper book	KG	Suburban	0.0049	0.0057	-14.0%
8	Life-Cycle	Other	Energy Use	Desktop PC	Percent	NA	0.89	1	-11.0%
8	Production	Other	Energy Use	Desktop PC	MJ	NA	5250	5833	-10.0%
8	Transportation	Other	Energy Use	Desktop PC	MJ	NA	86	165	-47.9%
8	Warehousing	Other	Energy Use	Desktop PC	MJ	NA	0.9	6	-85.0%
10	Transportation	B-2-B	SO2 eq	NA	Percent	Urban	0.92	1	-8.0%
13	Transportation	Other	Energy Use	NA	Percent	NA	0.95	1	-5.0%
14	Transportation	B-2-C	CO2-eq	Parcel	G	Suburban	130	2769.5	-95.3%
18	Life-Cycle	B-2-C	CO	Desktop PC	Mt	Suburban	21.684	41.07	-47.2%
18	Life-Cycle	B-2-C	CO	Desktop PC	Percent	Suburban	0.529	1	-47.1%
18	Life-Cycle	B-2-C	CO2-eq	Desktop PC	Mt	Suburban	616.3	873.8	-29.5%
18	Life-Cycle	B-2-C	CO2-eq	Desktop PC	Percent	Suburban	0.71	1	-29.0%
18	Life-Cycle	B-2-C	Energy Use	Desktop PC	Percent	Suburban	0.5604	1	-44.0%
18	Life-Cycle	B-2-C	Energy Use	Desktop PC	TJ	Suburban	26.938	48.07	-44.0%
18	Life-Cycle	B-2-C	N2O	Desktop PC	Mt	Suburban	6.27	10.51	-40.3%
18	Life-Cycle	B-2-C	N2O	Desktop PC	Percent	Suburban	0.597	1	-40.3%

20	Transportation	B-2-C	CO	Various	KG	Urban	1996	15644	-87.2%
20	Transportation	B-2-C	CO2-eq	Various	Mt	Urban	1687	4499	-62.5%
20	Transportation	B-2-C	N2O	Various	KG	Urban	72	117	-38.5%
20	Transportation	B-2-C	Other	Various	VMT	Urban	1814552	14620087	-87.6%
30	Life-Cycle	B-2-C	Energy Use	Paper book	MJ	NA	91	93	-2.2%
30	Packaging	B-2-C	Energy Use	Paper book	MJ	NA	13	4	225.0%
30	Packaging	B-2-C	Energy Use	Paper book	MJ	Rural	13	1.5	766.7%
30	Packaging	B-2-C	Energy Use	Paper book	MJ	Suburban	13	1.5	766.7%
30	Packaging	B-2-C	Energy Use	Paper book	MJ	Urban	13	1.5	766.7%
30	Production	B-2-C	Energy Use	Paper book	MJ	NA	18	25	-28.0%
30	Transportation	B-2-C	Energy Use	Paper book	MJ	NA	60	65	-7.7%
30	Transportation	B-2-C	Energy Use	Paper book	MJ	Rural	4.6	21.74	-78.8%
30	Transportation	B-2-C	Energy Use	Paper book	MJ	Suburban	0.99	10.4	-90.5%
30	Transportation	B-2-C	Energy Use	Paper book	MJ	Urban	0.225	0.026	765.4%
31	Life-Cycle	B-2-C	CO2-eq	Paper book	Mt	Suburban	1388	1518	-8.6%
31	Life-Cycle	B-2-C	CO2-eq	Paper book	Percent	Suburban	0.91	1	-9.0%
31	Life-Cycle	B-2-C	Energy Use	Paper book	Percent	Suburban	0.84	1	-16.0%
31	Life-Cycle	B-2-C	Energy Use	Paper book	TJ	Suburban	21	25	-16.0%
31	Life-Cycle	B-2-C	Waste	Paper book	Mt	Suburban	37	48	-22.9%
31	Life-Cycle	B-2-C	Waste	Paper book	Percent	Suburban	0.77	1	-23.0%
31	Packaging	B-2-C	CO2-eq	Paper book	Mt	Suburban	192	84	128.6%

31	Packaging	B-2-C	Energy Use	Paper book	TJ	Suburban	2.7	1.17	130.8%
31	Packaging	B-2-C	Waste	Paper book	Mt	Suburban	8.1	3.5	131.4%
31	Production	B-2-C	CO2-eq	Paper book	Mt	Suburban	0	494	-100.0%
31	Production	B-2-C	Energy Use	Paper book	TJ	Suburban	0	9.426	-100.0%
31	Production	B-2-C	Waste	Paper book	Mt	Suburban	0	35.8	-100.0%
31	Transportation	B-2-C	CO2-eq	Paper book	Mt	Suburban	1196.2	940.4	27.2%
31	Transportation	B-2-C	Energy Use	Paper book	TJ	Suburban	18.23	14.6	24.9%
31	Transportation	B-2-C	Waste	Paper book	Mt	Suburban	29.1	8.5	242.4%
34	Life-Cycle	B-2-C	CO2-eq	Paper book	Mt	Suburban	1963	1998	-1.8%
34	Life-Cycle	B-2-C	CO2-eq	Paper book	Percent	Suburban	0.98	1	-2.0%
34	Life-Cycle	B-2-C	Energy Use	Paper book	Percent	Suburban	0.91	1	-9.0%
34	Life-Cycle	B-2-C	Energy Use	Paper book	TJ	Suburban	30	33	-9.1%
34	Life-Cycle	B-2-C	Waste	Paper book	Mt	Suburban	58	66	-12.1%
34	Life-Cycle	B-2-C	Waste	Paper book	Percent	Suburban	0.88	1	-12.0%
34	Packaging	B-2-C	CO2-eq	Paper book	Mt	Suburban	254	84	202.4%
34	Packaging	B-2-C	Energy Use	Paper book	TJ	Suburban	3.6	1.2	200.0%
34	Packaging	B-2-C	Waste	Paper book	Mt	Suburban	10.7	3.5	205.7%
34	Production	B-2-C	CO2-eq	Paper book	Mt	Suburban	453	949	-52.3%
34	Production	B-2-C	Energy Use	Paper book	TJ	Suburban	7	16.45	-57.4%
34	Production	B-2-C	Waste	Paper book	Mt	Suburban	17	53	-67.9%

34	Transportation	B-2-C	CO2-eq	Paper book	Mt	Suburban	1256	965	30.2%
34	Transportation	B-2-C	Energy Use	Paper book	TJ	Suburban	19.2	15	28.0%
34	Transportation	B-2-C	Waste	Paper book	Mt	Suburban	30.4	9.1	234.1%
40	Life-Cycle	B-2-C	Energy Use	Desktop PC	MJ	Suburban	3605	3640	-1.0%
44	Transportation	B-2-C	CO2-eq	Grocery	Percent	Suburban	0.475	1	-52.5%
45	Life-Cycle	B-2-C	CO	DVDs	G	Suburban	2.54	2.96	-14.2%
45	Life-Cycle	B-2-C	CO2-eq	DVDs	G	Suburban	3450	5770	-40.2%
45	Life-Cycle	B-2-C	Energy Use	DVDs	MJ	Suburban	68.2	101.3	-32.7%
45	Life-Cycle	B-2-C	SO2 eq	DVDs	G	Suburban	7.4	12.9	-42.6%
48	Transportation	B-2-C	Energy Use	Grocery	Mt	Urban	0.29	1	-71.0%
48	Transportation	B-2-C	Other	Grocery	Mt	Urban	0.61	1	-39.0%
49	Life-Cycle	B-2-C	CO2-eq	Grocery	KG	Urban	0.15	0.24	-37.5%
50	Life-Cycle	B-2-C	CO2-eq	DVDs	KG	Urban	0.21	3.23	-93.5%
50	Life-Cycle	B-2-C	Energy Use	DVDs	MJ	Urban	4.95	48.6	-89.8%
50	Packaging	B-2-C	CO2-eq	DVDs	Mt	Urban	25.16	100.64	-75.0%
50	Packaging	B-2-C	Energy Use	DVDs	TJ	Urban	0.43	1.73	-75.1%
50	Transportation	B-2-C	CO2-eq	DVDs	Mt	Urban	3.78	393.49	-99.0%
50	Transportation	B-2-C	Energy Use	DVDs	TJ	Urban	0.05	5.69	-99.1%
51	Life-Cycle	B-2-C	CO2-eq	Flash drive	G	Suburban	2200	2800	-21.4%
51	Life-Cycle	B-2-C	Energy Use	Flash drive	MJ	Suburban	31	43	-27.9%
52	Life-Cycle	B-2-C	CO2-eq	DVDs	G	Suburban	2050	3200	-35.9%
52	Life-Cycle	B-2-C	Energy Use	DVDs	MJ	Suburban	33	53	-37.7%
53	Transportation	B-2-C	Other	Various	Percent	Suburban	0.9961	1	-0.4%
54	Transportation	B-2-C	CO2-eq	Cloth	KG	Urban	0.232	2.454	-90.5%
55	Life-Cycle	B-2-C	Energy Use	Paper book	MJ	Rural	7.6	7.2	5.6%

55	Life-Cycle	B-2-C	Energy Use	Paper book	MJ	Suburban	5.6	5.2	7.7%
55	Life-Cycle	B-2-C	Energy Use	Paper book	MJ	Urban	5	2.9	72.4%
55	Packaging	B-2-C	Energy Use	Paper book	MJ	NA	3.9	0.8	387.5%
55	Transportation	B-2-C	Energy Use	Paper book	MJ	Rural	2.8	5.3	-47.2%
55	Transportation	B-2-C	Energy Use	Paper book	MJ	Suburban	0.63	3.34	-81.1%
55	Transportation	B-2-C	Energy Use	Paper book	MJ	Urban	0.16	0.942	-83.0%
60	Transportation	B-2-C	CO2-eq	Paper book	KG	Urban	0.058	0.052	11.5%
60	Transportation	B-2-C	Energy Use	Paper book	MJ	Urban	1.651	1.58	4.5%
65	Life-Cycle	B-2-C	CO2-eq	Parcel	KG	Suburban	0.18	0.1	80.0%
66	Life-Cycle	B-2-C	CH4	Telework	KG	Urban	0.01	0.75	-98.7%
66	Life-Cycle	B-2-C	CO2-eq	Telework	KG	Urban	1.3	608	-99.8%
66	Life-Cycle	B-2-C	CO2-eq	Newspaper	KG	Urban	5	158	-96.8%
66	Life-Cycle	B-2-C	SO2 eq	Telework	KG	Urban	9	254	-96.5%

Appendix 6: Distribution of product types in the retrieved data

Product	Count
Paper book	52
Desktop PC	13
DVDs	12
Various	5
Grocery	4
Telework	3
Parcel	2
Flash drive	2
NA	2
Newspaper	1
Cloth	1

Appendix 7: Distribution of population density areas in the retrieved data

Geography	Count
Suburban	58
Urban	25
NA	10
Rural	4