DEVELOPMENT AND APPLICATION OF FLOOD FOOTPRINT ANALYTICAL MODEL IN ASSESSING ECONOMIC IMPACT TO FLOODING EVENTS

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ABSTRACT OF THESIS:

This thesis presents a methodological approach, the flood footprint framework, to capture the total economic costs of flooding events, as some of the most damaging climatic disasters. Economic costs are constituted by physical destruction, and all cascaded disruptions caused by the direct destruction.

The method uses the fundamentals of Input-Output modelling, which is founded on the conceptualisation of the circular flow of the economy, representing the complex transactions between producers and intermediate and final consumers, for each sector, in an algebraic array. The solution of the equations' system allows quantification of direct and indirect impacts along the value chain from changes in final demand. The flood footprint model further extends to capture changes in production due to the distortions of the economic equilibrium caused by flooding events, and to simulate the economy's recovery. Sources of flooding disruption within the model arise from capital constraints, disruptions to labour force, and behavioural changes in final consumption.

The method was applied to four case studies. The outcomes support the lesson that losses from a disaster are exacerbated and disseminated to other economies throughout economic mechanisms, and those knock-on effects (or indirect damages) constitute a substantial proportion of total economic losses, where non-directly flooded sectors might be also severely affected.

The main implications for adaptation strategies are the review of the dynamics of direct and indirect damages and to unveil vulnerable hotspots along the value chain. This would allow an efficient allocation of investment resources and minimisation of socioeconomic damages during post-flood economic recovery.

The key contribution of this thesis is a comprehensive methodology for assessing the total economic impacts of flooding events, considering elements that had not been taken into account together before, by incorporating multidisciplinary techniques for evaluation and projection of future scenarios, and bringing the analysis to a multiregional (global) scale.

Contents

List of Abbreviations 11

Chapter 1 Introduction 13

1.1 Climate Change and natural hazards 13

1.2 Cost of climate extreme events 14

1.3 Direct and indirect costs in economic impact analysis 15

1.4 Research motivations...16

1.5 Aim and objectives...17

1.6 Organisation of the thesis...18

Chapter 2 Literature Review 21

2.1 Past research in studying the cost of natural hazards 21

2.1.1 Economic damages assessment (direct and indirect costs)...................................23

2.1.2 General equilibrium costs 24

2.2 Methodologies used in Impact Analysis 25

2.2.1 Input Output model 25

2.2.2 Computable General Equilibrium models..26

2.2.3 Econometric models 27

2.2.4 Hybrid models..28

2.2.5 Survey-based impact analysis 28

2.2.6 Choosing an Analytical Framework...28

2.3 Input Output analysis approach...30

2.3.1 Standard Input Output model...32

2.3.2 Applications to impact assessment of natural disasters..35

2.3.3 Leontief Price Model based on Monetary Values...36

2.3.4 Leontief Price Model based on physical data 38

2.3.5 Supply IO model. The Ghosh Model 41

2.3.6 Reinterpretation as a price model 42

2.3.7 Backward and forward linkages..44

2.3.8 Backward linkages..44

2.3.9 Forward linkages 46
2.3.10 'Net' backward linkages 47
2.3.11 Hypothetical Extraction 49
2.3.12 Applications in natural disasters 50
2.4 Environmental Input Output modelling 51
2.5 Economic-Ecological IO model 53
2.6 MRIO and IRIO analysis with Environmental Extensions 55
2.6.1 Interregional Input Output Model (IRIO) 56
2.6.2 Multiregional Input Output Model (MRIO) 59
2.7 IO approach for impact assessment of climate extreme events. Indirect cost appraisal 65
2.7.1 Modelling risk 65
2.7.2 Time-dynamic extensions 65
2.7.3 Modelling Imbalances 66
2.7.4 Recent work on impact assessment by using IO modelling 68
Chapter 3 Methodology. Flood Footprint Assessment Framework 70
3.1 Standard Flood Footprint model 71
3.1.2 Post-disaster recovery process 76
3.2 Flood Footprint modelling outcomes 82
3.3 Flowchart for flood footprint modelling 82
3.4 Standard Flood Footprint model for multiple regions 89
3.4.1 Recovery process and the capital matrix 90
3.4.2 Total Flood Footprint for multiple regions 92
3.5 Methodology for the multi-regional Flood Footprint model 92
3.5.1 Production constraints 95
3.5.2 Labour productivity constraints 95
3.5.3 Capital production constraints 95
3.5.4 Changes in final demand 96
3.5.5 Post-disaster recovery process 96
3.6 Regionalisation of IO technical coefficients 99
3.7 Model limitations 101
3.7.1 Model rigidities 101
3.7.2 Model Parameters 102

3.7.3 Information uncertainties 103

3.7.4 Model reliability 104

3.7.5 Model robustness 104

Chapter 4 Flood Footprint of the 2007 Floods in the UK: The case of the Yorkshire and The Humber region 106

4.1 Data gathering and codification 107

4.1.1 Economic data 107

4.1.2 Disaster Data 108

4.2 Results 110

4.2.1 Total Economic Loss for Yorkshire and The Humber region 110

4.2.2 Economic Recovery 111

4.2.3 Sectoral Analysis 113

4.3 Sensitivity analysis 114

4.3.1 Changes in labour parameters 115

4.3.2 Changes in final demand 116

4.4 Summary 117

Chapter 5 Single-regional modelling of multiple regions. 2009 Central Europe flooding and 2010 Xynthia windstorm cases 118

5.1 Exposure to natural disasters in Europe 119

5.1.1 Data 120

5.1.2 Disaster damages 120

5.1.3 Damage functions 121

5.1.4 IO tables 122

5.1.5 Capital matrix 122

5.1.6 Labour damage 124

5.2 Results 125

5.2.1 2009 Central European Flood 125

5.2.2 2010 Windstorm Xynthia 133

5.3 Summary 141

Chapter 6 Multi-regional flood footprint analysis: case study of Rotterdam, The Netherlands. 143

6.1 Rotterdam 144

6.1.1 Historical flood risk context 145

6.1.2 Urban planning context 146

6.1.3 Institutional context 146

6.1.4 Data 146

6.1.5 Disaster information 147

6.1.6 Economic information 148

6.1.7 Economic data on Rotterdam 149

6.2 Results. Multiregional Flood Footprint assessment 149

6.2.1 Direct and Indirect damage 150

6.2.2 Recovery path 151

6.2.3 Regional distribution 152

6.2.4 Sectoral distribution 152

6.2.5 Sensitivity Analysis 153

6.3 Summary 155

Chapter 7 Flood footprint analysis and application in a Blue-Green infrastructure approach: case of Newcastle city 157

7.1 BGI for flood risk management 158

7.2 Methodology 160

7.2.1 The Multiple Benefits Toolbox 161

7.2.2 Nexus between the MBT and the flood footprint models 164

7.3 Data gathering and codification 164

7.3.1 Hazard information 165

7.3.2 Infrastructure information 165

7.3.3 Damage functions 166

7.3.4 Economic data for flood footprint model 167

7.3.5 Disaster Data 168

7.4 Results 168

7.4.1 Flood Footprint 169

7.4.2 BGI benefits 171

7.4.3 Sectoral distribution of benefits 172

7.4.4 Sensitivity Analysis 173

7.5 Summary 175

Chapter 8 CONCLUSIONS 177

8.1 Contribution to knowledge 177
8.2 Key method development 177
8.3 Summary of key findings and policy implications 179
8.4 Implications for stakeholders and policy makers 181
8.5 Limitations of the study 182
8.6 Future research 182
REFERENCES 184
Appendix 193

List of figures

Figure 1.1 Number of Climate-related disasters worldwide (1980 – 2011) 13
Figure 2.1 Input Output table 32
Figure 2.2 Economic-Ecological Dynamics 53
Figure 3.1 Modelling process for Flood Footprint appraisal 83
Figure 3.2 MRIO table for three regions and two sectors each 93
Figure 4.1 Yorkshire and The Humber region within the UK 107
Figure 4.2 Flood Footprint. Damage composition (£million) 111
Figure 4.3 Recovery process 112
Figure 4.4 Sectoral distribution of damage 113
Figure 4.5 The most affected sectors by different damage categories: Direct and Indirect damage 114
Figure 4.6 Sensitivity analysis for labour parameters 115
Figure 4.7 Sensitivity analysis for final demand parameters 116
Figure 5.1 Natural disasters in EEA member countries from 1980 to 2009 119
Figure 5.2 Regions under influence of heavy rain and river overflows during 2009 summer floods 125
Figure 5.3 Value of material damages by country 126
Figure 5.4 Economic recovery path for 2009 flood case study 126
Figure 5.5 Regional distribution of damages of the 2009 flooding in Central Europe 127

Figure 5.6 Distribution of direct and indirect damage by economic sector 129

Figure 5.7 National distribution of direct and indirect damage by industrial sector.............. 130

Figure 5.8 Sensitivity analysis, by sector 132

Figure 5.9 Sensitivity analysis by country 132

Figure 5.10 Regions under influence of the 2010 Xynthia Windstorm 133

Figure 5.11 Economic recovery path for 2010 Windstorm Xynthia case study 134

Figure 5.12 Regional distribution of damages caused by the 2010 Xynthia windstorm 135

Figure 5.13 Distribution of direct and indirect damage by economic.................................. 137

Figure 5.14 National distribution of direct and indirect damage by industrial sectors........... 137

Figure 5.15 Sensitivity analysis by sector 140

Figure 5.16 Sensitivity analysis by country... 140

Figure 6.1 Location of the metropolitan area of Rotterdam 144

Figure 6.2 Multiregional Flood Footprint (US$ million) 150

Figure 6.3 Recovery path.. 151

Figure 6.4 Indirect damage by country.. 152

Figure 6.5 Flood Footprint in The Netherlands.. 153

Figure 6.6 Sensitivity Analysis by country 154

Figure 6.7 Sensitivity Analysis by sector 155

Figure 7.1 Benefit Curve showing the derivation of Benefit score and potential benefit....... 162

Figure 7.2 Example damage probability curve 164

Figure 7.3 Newcastle Upon Tyne. Urban core (in red) and the City's administrative boundary (in black).. 165

Figure 7.4 Depth damage curves used in the MBT 166

Figure 7.5 Flood Footprint for Grey Infrastructure & Blue Green Infrastructure for all return periods.. 170

Figure 7.6 BGI benefits (avoided direct and indirect costs) 171

Figure 7.7 BGI benefits by industry.. 172

Figure 7.8 Sensitivity analysis by return period 174

Figure 7.9 Sensitivity analysis for indirect benefits 174

Figure 7.10 Sensitivity analysis by industry group 175

List of tables

Table 4.1 EAV for the 2007Floods in Y&H 109

Table 5.1 Industrial sectors for analysis 120

Table 5.2 Availability on capital data for affected countries 123

Table 5.3 Sectors involved in capital formation 124

Table 7.1 Flood Footprint for Grey (G) and BG infrastructure (£million) 169

Table 8.1 Summary of results of case studies 180

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List of Abbreviations

AFLQ	Augmented Flegg Location Quotients
ARCC	Adaptation and Resilience in a Changing Climate
ARIO	Adaptive Regional Input Output
BASE	Bottom-up Climate Adaptation Strategies towards Sustainable Europe
BDI	Basic Dynamic Inequalities
BGC	Blue Green Cities
BGI	Blue Green Infrastructure
BGI	Blue-green infrastructure
CGE	Computable General Equilibrium models
CILQ	Cross-industry Location Quotients
CityCAT	City Catchment Analysis Tool
DIIM	Dynamic Inoperability IO model
EAM	Event Account Matrix
EAV	Event Account vector
EEA	European Environmental Agency
EM-DAT	Disaster Database
EPSRC	UK’s Engineering and Physical Science Research Council
EU	European Union
FF	Flood Footprint
FLQ	Flegg Location Quotients
GDP	Gross Domestic Product
GI	Grey Infrastructure
GI	Gross Infrastructure
GIS	Geographical Information System
GVA	Gross Value Added
GVA	Gross Value Added

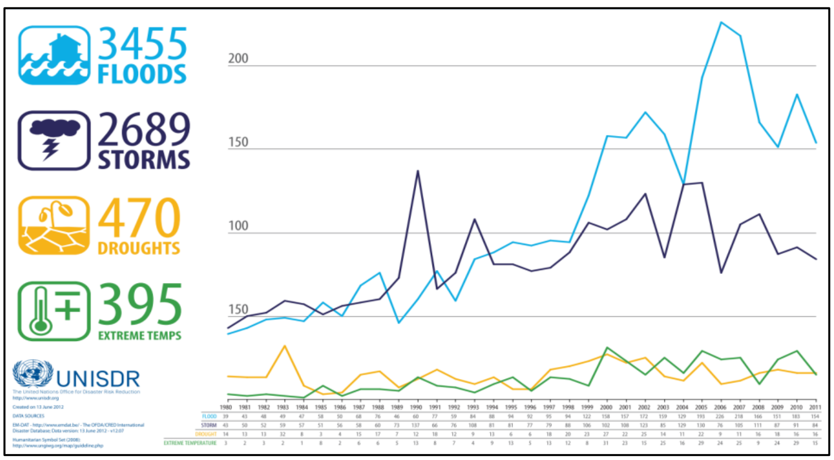
IO	Input Output
IPCC	The Intergovernmental Panel on Climate Change
IRIO	Interregional IO model
IT	Information and Technology
JCP	Journal of Cleaner Production
JRC	Joint Research Centre of the European Commission
MBT	Multiple Benefits Toolbox
MIIM	Multiregional Inoperability Input-output Model
MRFF	Multiregional flood footprint
MRFF	multi-regional flood footprint
MRIO	Multi-Regional Input Output
NATHAN	Natural Hazards Assessment Network
NHESS	Natural Hazard and Earth System Science
NUTS	Nomenclature of territorial units for statistics
OS map	Ordnance Survey Map
PAD	Public Administration and Defence
REIM	Regional econometric input–output model
RIMS II	Regional Input-Output Multiplier System
SAM	Social Accountability Matrix
SDIIM	Supply-Driven Dynamic Inoperability Input-Output Price Model
SIM	Sequential Inter-Industry Model
SLQ	Simple location quotients
SuDS	Sustainable Drainage Systems
UK	The United Kingdom
UNISDR	United Nations Office for Risk Reduction
UNSD	United Nations Statistical Commission
US	The United States
VA	Value Added
WIOD	World Input-Output Database
Y&H	Yorkshire & The Humber

Chapter 1 Introduction

1.1 Climate Change and natural hazards

Extreme natural hazards have increased in both intensity and frequency in recent decades, with adverse effects on societies all around the world. The scientific evidence agrees that these are manifestations of climate change that, in its anthropogenic component, is a consequence of the accumulation of greenhouse gases in the atmosphere. The Government Office of Science in the UK points out that the hydro-meteorological hazards nowadays are six times more frequent than in the past half century. The Figure 1.1 from the United Nations Office for Risk Reduction (UNISDR) shows that tendency worldwide in the last decades, and the trend is expected to increase (Guha-Sapir & Hoyois, 2012; Okuyama, 2009; Veen & Logtmeijer, 2003).

Figure 1.1 Number of Climate-related disasters worldwide (1980 – 2011)



Source: UNISDR (2016)

At the same time, as the increase in the natural hazards frequency, population around the world have rapidly agglomerated in urban areas, concentrating nowadays more than half of the population worldwide, with this proportion expected to reach 66% by 2030 (IPCC, 2014; United Nations, 2014).

This increases the exposition of population to natural hazards. According to the Joint Research Centre (JRC) of the European Commission, the exposure of people and property to natural hazards[1] has doubled in the last 40 years '*mostly due to urbanisation, population growth and socioeconomic development*' (Pesaresi et al. 2017). On its part, the UNISDR states that growing population in urban settlements is faster in developing countries. As instance, medium size cites (with more than 500,00 people) and megacities (with more than 10 million people) in these countries have multiplied by six in developing countries since 1950. The low levels of economic development in these areas have increased the vulnerability in the face of natural hazards (Gencer, 2013). In the period 1970-2008, 95% of deaths caused by natural disasters occurred in developing countries.

Around two thirds of the urban population around the world live in coastal areas, and the share is expected to reach three quarters by 2025. The risk of natural disasters in these urban areas is exacerbated by climate change, with a 99% of likelihood of increasing frequency in storms, rivers' overflows, and the rise of sea levels. The economic costs from natural disasters worldwide have also increased (IPCC, 2012).

The UNISDR, with data from the International Disasters Database (EM-DAT)[2] states that in the last decade natural disasters around the world caused economic losses at US$1.4 trillion, affected around 1.7 billion people and caused the deaths of 0.7 million people, and around 87% of the costs by 2014 where caused by climate-related disasters (UNISDR, 2014).

These situations urge for adaptation strategies owing to the increasing risks, and economic losses (A. Z. Rose, 2004).

1.2 Cost of climate extreme[3] events

A climatic extreme event or natural disaster occurs when a natural hazard (e.g. a hurricane, windstorm, earthquake, etc.) interrupts the normal functioning of a socioeconomic system (Okuyama (2009). The magnitude of the consequences depends on several factors: the hazard characteristics (e.g. intensity and duration), the geographical, climate and sociodemographic characteristics of the impacted region, and to a large degree on the adaptation strategies or human response to the disaster (IPCC, 2012).

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[1] In the 2017 Atlas of the Human Planet, the JRC considers the exposure to the six major natural hazards: earthquakes, volcanos, tsunamis, tropical cyclone winds, tropical cyclone storm surge and floods.
[2] EM-DAT. The International Disaster Database. Centre for Research on the Epidemiology of Disasters – CRED: http://www.emdat.be/
[3] Along this thesis, the terms 'climate extreme event' and 'natural disaster' are used indistinctly.

Natural disasters impose severe damages to societies by inducing human losses and health problems (both physical and psychological), environmental and cultural damages, and economic damages and disruptions. The task of quantifying the damages is challenging as there is no agreement on a methodology capable of enclosing all damage types (Greenberg, Lahr, & Mantell, 2007; IPCC, 2012) .

The research on economic impacts of natural disasters offers a range of methodological tools to account for the socioeconomic damages of climatic extreme events. Although only a limited range of damages are considered, the economic evaluation of the damages provides a robust perspective of the consequences in the impacted society (Guha-Sapir & Hoyois, 2012). The main advantage of economic impact assessment is the possibility to account for the damages induced by direct destruction and the subsequent costs to the society owing to the disruptions triggered by the former.

1.3 Direct and indirect costs in economic impact analysis

The research on economic impacts of natural disasters groups the costs in different categories, according to their sources. The different categories can be grouped in two main groups: direct and indirect damages[4].

In general, the direct costs refer to the quantification of the physical damages directly caused by the hazard, such as damages to roads, railways, houses, people casualties, etc, which are traditionally estimated based on the value of reposition or the commercial value of the damaged assets (Stephane Hallegatte & Przyluski, 2010; J. R. Santos & Rehman, 2012; Veen, 2004; Veen & Logtmeijer, 2003). Until recently, the economic impact of the natural disasters had been solely focused on the assessment of direct damages, or more specifically, on the financial costs of these physical damages.

However, the damages to physical assets can further trigger a series of economic disruptions that spread along the value chain and interfere with the production flows of the whole impacted economy and even to other linked economies outside the impacted region. On the other hand, changes in consumption patterns of the population in the affected region may also cause economic contractions. All the production flows that are lost owing to the disruptions caused by

[4] In this thesis, the terms economic damage and economic costs are equivalents.

a natural hazard are considered within the indirect damages (Okuyama, 2009; A. Z. Rose, 2004; Veen, 2004).

The indirect damages had not been explicitly considered in the impact assessment until recently. However, a complete assessment of the economic impacts of natural disasters must consider the indirect damages, as they may represent a considerable proportion of the total costs of a natural disaster, and provide information on how the damages spread over the whole economy.

1.4 Research motivations

Given the fact that climate is changing with adverse consequences to life on earth, and this tendency is expected to be exacerbated in future decades despite any climate change mitigation actions taking place today, climate change adaptation strategies are urgently needed to assure the preservation of life as it is known nowadays.

The motivation underlining this thesis was to focus mainly on the consequences of climate change to societies. Unfortunately, the development of societies around the world is mainly driven by economic interests, especially those which contribute more to climate change. This, on the other hand, has largely inspired us to raise awareness, in economic terms.

Owing to the above, it was the intention to contribute in better informing on the economic repercussions of climate change. I believe it is urgent for societies to develop adaptation strategies to minimise the adverse impacts of climatic extreme events. However, the implementation of adaptation strategies normally lies on their economic viability, which is traditionally based on a cost-benefit analysis. Thus, a sound assessment of the full economic costs of a natural disaster[5] would assist in the development of effective adaptation strategies.

That is the motivation to contribute with a prompt and accurate estimation of damages so that policy makers can take better-informed decisions to develop strategies for climatic risk management. All with the final goal of reducing the harmful consequences of climate change to societies.

The development of the new methodology must incorporate elements to consider diverse aspects of economic impact analysis that had not been previously incorporated in an integrated

[5] In this thesis the terms ‘climate extreme event’ and ‘natural disaster’ are equivalent.

model. These comprises the multiregional dimension of the analysis, the dynamic-time recovery, the effects from labour disruptions and residential damages, the behavioural change on final consumption, the transition from capital recovery investment to the recovery of productive capacity.

The analysis focuses on flooding events, since they represent the events that have increased more in the last decades with the highest costs for the societies.

The following four common questions summarise the rationale of the research that this thesis follows:

- **What?** Assessing the total economic impact of natural disasters, considering cascade effects on regions and countries over time.

- **How?** With a Multi-Regional Input Output (MRIO) based model, which evaluates the costs from direct destruction of a natural disaster, and considers the shortages in production capacities and economic imbalances to evaluate the economic costs from the indirect consequences of the direct destruction.

- **Why?** Because there are theoretical and practical gaps in assessing the total economic impact of natural disasters, especially in accounting for constrains in the supply chain from damages in basic productive factors (capital and labour); as well as in the economic dynamics over the recovery time.

- **What for?** To provide prompt and accurate information so that policy makers can take better-informed decisions to develop strategies for climate risk management. All with the final goal of reducing the harmful consequences of climate change to societies.

1.5 Aim and objectives

This thesis intends to contribute towards a more accurate estimation of the total economic costs of natural disasters, throughout the development and real case applications of a methodology that extends upon previous research.

The overarching aim is to develop a useful methodology to assess the economic costs from physical damages arising from a climatic extreme event to understand how an economic shock from a flooding event generates costs that are transmitted and propagated to wider economic systems. The evaluation of these costs constitutes the *flood footprint*.

In order to achieve this overreaching aim, four objectives are set as below.

Objective 1: Developing the flood footprint modelling framework based on earlier research efforts in Stéphane Hallegatte (2008) and (Li, Crawford-Brown, Syddall, & Guan, 2013) and illustrate step-by-step the mathematical development of the analytical framework.

Objective 2: Extending the flood footprint framework from single regional model to a multiregional model, which allows examining the cascading effects beyond physically impacted regions.

Objective 3: Inter-connecting flood footprint model with engineering models to enable better capture of physical damage and the analysis of projected scenarios. The application of the case study is more practical use.

Objective 4: Applying each of the stages of the modelling development to practical cases, either past events or projected scenarios.

1.6 Organisation of the thesis

The literature is reviewed in Chapter 2. It starts with a discussion about the research on estimating the economic impact of natural disasters. It identifies the type of costs associated with the destruction from a natural hazard. After that, a revision will be conducted about economic imbalances arising from the shock, and the efforts for quantifying the secondary consequences to the whole economy. Later, the chapter provides a summary of the economic techniques most widely used in the appraisal of the damages. These include extensions of models base on Input-Output (IO) modelling, Computable General Equilibrium (CGE) models, Econometric models, Social Accountability Matrices (SAM), survey-based analysis and hybrid models. As the modelling of this thesis is based on the IO approach, the last section of the chapter expands on the IO methodology and its applications in the impact assessment of climatic extreme events.

Chapter 3 presents the stages of the methodology (Objective 1), the single-regional flood footprint model, which is based on the Adaptive Regional Input Output (ARIO) model developed in Stéphane Hallegatte (2008) and extended in Li et al. (2013). And further development for multiple regions analysis, and finally the Multi-Regional Flood Footprint model.

Chapters 4, 5, 6 present, individually, the applying of the different stages in the development of the methodology towards the multiregional flood footprint model, related case study.

Chapter 4 applies the single-regional flood footprint model to assess the economic impacts of the 2007 summer floods in the UK (Objective 4). The analysis is over the region of Yorkshire and The Humber. This constitutes the first application of the model to a real (past) case, highlighting the needs and main barriers for the model applications. Basically, the main barrier and source of uncertainty come from the lack of data related with the direct consequences of the natural disaster. The application on a real case also serves to calibrate the parameters of the model and check on their influence in the results. The model is especially sensitive to changes in the parameters of labour constraints. This case study was part of the research project 'SESAME. Finding ways of promoting SME adaptation to flood risk', founded by the UK's Engineering and Physical Science Research Council (EPSRC) under grant EP/K012770/1.[6]

The work of Chapters 3 and 4 has been integrated into a journal paper submitted to the Journal of Cleaner Production (JCP), which has been accepted and published: (https://doi.org/10.1016/j.jclepro.2017.09.016).

Chapter 5 applies the three main contributions to the modelling in section 3.4 (Objective 4). First, the model is adapted to consider the damages in multiple regions at the same time. At this stage, the appraisal in each region is based on the single-regional flood footprint model. Despite this, the model was able to provide a broad picture on the damages from (two different) climatic extreme events over all the regions directly affected. Secondly, the model was successfully applicable to two different climate extreme events: the major floods in Central Europe in the summer of 2009, and the Windstorm Xynthia in 2010 affecting Western and Southern Europe. Finally, the concept of the capital matrix is incorporated to the flood footprint modelling. This element brings higher consistency to the model in two aspects: in the dynamics of the recovery over time, and in the transition from a stock variable (the investment in capital for reconstruction) to a flow variable (the gradual recovery in production flow). The analysis of these case studies took part within the project 'Climate extremes: defining a pilot approach on

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[6] SESAME project website: http://sesame.uk.com/economics-impact/

estimating the direct and indirect impacts on economic activity' for the European commission under the contract reference CLIMA.C.3/SER/2013/0019.

Chapter 6 applies the last stage of the model (so far) with the development for a multiregional analysis (Objectives 2 and 4). The case study benefited from the data provided within the project of which it formed part, the 'Bottom-up Climate Adaptation Strategies towards a Sustainable Europe (BASE)' project[7] for the European Commission with the Grant Agreement No. 308337, which is part of the broader Collaborative project (IP) FP7-ENV-2012-two-stage, Subsidy for Environment (including climate change). Taking part in this project allowed for the analysis of a projected climate extreme event that incorporates the forecast on future climate change, and the forecast on socioeconomic development in the city of Rotterdam, The Netherlands. The chapter shows how the consequences of a climate extreme event in a city affects the national economy, and how these disruptions propagates worldwide through the economic interconnections.

Chapter 7 represents the last of the analytical chapters (Objectives 3 and 4). In this chapter, the flood footprint model is integrated with a model based on Geographical Information Systems (GIS) to build a hybrid model capable to evaluate the economic benefits derived from the (hypothetical) implementation of strategies for climate risk management, which in this case is based on the incorporation of Blue-Green Infrastructure (BGI) into an urban area. The integration of the flood footprint framework (a model for economic appraisal) with other technologies, such as engineering flood models, GIS models, and the depth damage functions, opens a huge range of possibilities for the applications and further development of the methodology. The case study was part of the Blue Green Cities (BGC) project[8] founded by the UK Engineering and Physical Sciences Research Council (EPSRC Project EP/K013661/1).

Finally, Chapter 8 presents a brief discussion on the results and shows how the overarching goal and the objectives of the research are reached. It also presents the main contribution of the research to the academic knowledge and implications for public policy and stakeholders.

[7] BASE project website: http://base-adaptation.eu/

[8] BGC project website: http://www.bluegreencities.ac.uk/index.aspx

Chapter 2 Literature Review

Chapter 2 offers an overview of the literature reviewed for this research. This includes two sets of literature. First, it was reviewed the literature related with the appraisal of economic damages caused by natural disasters. This encloses the main techniques used for this purpose, as well as the advantages and disadvantages presented by each of them. The critical review of this literature allowed to determine the modelling framework on which the research would be conducted. The chosen modelling framework is the IO model, as its characteristics well suit with the research challenges. Secondly, it is presented the basis of the modelling framework, and extensions made for adapting it to the appraisal of direct and indirect economic damages of natural disasters. It is extensively presented the IO model extensions that most commonly have been applied for these purposes. The literature review on IO modelling provides the theoretical basis for the methodology, in Chapter 3.

2.1 Previous research in studying the cost of natural hazards

The appraisal of the cost of natural disasters presents several difficulties that defining a single unit to represent the total damages is virtually impossible. How to combine, for example, the destruction of a cultural heritage building, with the loss of human lives, or with the destruction of a house? Concerning the secondary effects of the destruction, how to quantify the radiation pollution from damages to a nuclear reactor, with the loss in productivity because a factory outside of the impacted region cannot get the necessary inputs form an affected factory.

As the monetary value (or price) provides an accepted unit of value, economic theory has come up with several attempts to assign a monetary value (or price) to those non-tradable goods or services, such as cultural heritage assets or environmental services. However, the assessment of economic costs of all damages involved in a natural disaster presents several challenges. First, there is no direct way to assign a price to some of the assets destroyed during a disaster, especially to public goods or services, such as the environmental services, social health or historical legacy. This is because there is not a market for these types of products or the market fails to assign a perfect-competition market price.

Some economic techniques to measure the value of these services have been developed, such as the hedonic prices or contingence valuation approaches, which indirectly evaluates the value of goods and services for which there is not a market. However, this type of evaluation is usually left outside of the economic impact analysis of natural disasters, owing to the difficulties to carry out this type of analysis and the frequent biases in the results (Cochrane, 2004; Stephane Hallegatte & Przyluski, 2010; A. Z. Rose, 2004).

Secondly, the physical destruction usually triggers secondary effects in the environment, society and/ or economy, either in the impacted region or in regions that are more distant. Consider the mentioned case when a natural disaster damages a nuclear reactor and radiation spreads to contaminate distant regions; or the case where a factory producing aircraft engine parts (a highly specialised industry) is affected, so that the production of aircrafts in other parts of the world can be seriously affected. The quantification of these more complex effects is far more difficult, particularly when they affect non-tradable goods and services.

In summary, the quantification of the total damages, including those caused by the direct destruction and the secondary effects from that destruction, presents two main difficulties. First, it is practically impossible to account for all dimensions of damages. Secondly, even when there are some attempts to quantify the damages (e.g. casualties or destroyed biodiversity), it would be extremely complex and biased to combine these damages into a single unit.

In the practice, to simplify the task to measure the costs of a disaster, it has been traditionally accepted to make an economic appraisal of the damages (Crowther, Haimes, & Taub, 2007; A. Z. Rose, 2004). Although it is not a comprehensive measurement of the disasters' damages, it is useful in at least two ways. On the one hand, it provides a general idea about the amount, the location and distribution of the damages. On the other hand, the resources for adaptation (prior to the disaster) or for alleviation and reconstruction (after the disaster) are usually based on an economic analysis of the damages (Crowther & Haimes, 2010; Crowther et al., 2007; Greenberg et al., 2007; J. R. Santos & Haimes, 2004; J. R. Santos & Rehman, 2012).

With this, the task is simplified to the appraisal of the economic damages caused by a climatic extreme event.

2.1.1 Economic damages assessment (direct and indirect costs)

As previously mentioned, the damages from a disaster are composed of the direct destruction and the indirect consequences of that destruction. The impact assessment of economic damages[9] from natural disaster distinguishes between several categories of damages, but these can be grouped into two main categories: direct economic costs and indirect economic costs[10]. The direct costs account for the market value of the destroyed capital (a stock variable); and the indirect damages accounts for any kind of interruption to the production of goods and services (a flow variable) resulting from the direct damages (Okuyama, 2009; A. Z. Rose, 2004).

In practice, the direct costs refer to the damages or destruction to the physical infrastructure, such as houses, businesses buildings, hospitals, railways, roads, power stations, water treatment plants, etc. These are usually evaluated at market prices by insurance companies, government agencies or other institutions (Stephane Hallegatte & Przyluski, 2010; J. R. Santos & Rehman, 2012; Veen & Logtmeijer, 2003). Sometimes, the quantification of these damages is difficult, where secondary data or modelling estimations have to be used instead (Cole, 2003; Steenge & Bočkarjova, 2007). Recently, the use of GIS along with flood mapping and the ‘damage functions’ has increased the accuracy and efficiency of direct cost estimation. It also allows the possibilities of the analysis to future scenarios where several variables can be considered, such as climate change and socio-economic development (Veen, 2004).

On the other hand, the direct damages may have consequences that can spread through the whole economy and even to other regions’ economies that are not directly affected by the disaster event.

When damages induced by the impact of a natural disaster generates a malfunctioning in the economic system, some imbalances emerge between production capacity and demand that persist through time until the economic equilibrium is restored (Li et al., 2013). This may result in production bottlenecks and consumption behaviour changes (Stéphane Hallegatte, 2008). For instance, after the impact of a hurricane, some buildings are completely destroyed or

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[9] In this thesis, the terms ‘economic costs’, ‘economic losses’ and ‘economic damages’ are considered as equivalents.

[10] As this thesis focuses on the economic costs of the damages caused by a disaster, from here the direct economic costs and the indirect economic costs will be referred as direct costs (or damages) and indirect costs (or damages), respectively.

unavailable for use, and the cost of the building or the cost of repairing it would represent the direct costs of that damage (Cochrane, 1997, 2004; Okuyama, 2003; Veen, 2004). However, if the damaged building were a factory, all the lost production in the time the building is being repaired or reconstructed would represent the additional indirect costs. These costs can be spread in both directions, throughout forward and backward linkages (Okuyama, 2003).

In the case of forward effects, due to the interconnections between industrial sectors, businesses in other sectors that depend on inputs from the damaged sector will not be able to find alternative suppliers at the same price, at least in the short run, and as consequence they are going to be incapable of production at their normal output level. The length and severity of these disruptions in the economy depend mainly on the relations between the different economic sectors, and the consequences can be felt not only in the impacted region but also in other regions within the country or even in other regions of the world with economic linkages.

In the case of backward linkages, the reduction in production of the directly damaged sectors would, in turn, reduce the demand for their suppliers reducing their production as well, and so on. Again, this damages can be felt in other regions that are economically interconnected (Greenberg et al., 2007).

Furthermore, damages to infrastructure such as bridges or road networks, as well as residential damages, would induce constraints on the ability of the labour force to go to work. This would affect the productivity of those sectors with decreased labour force. As labour is one of the basic productive factors, the constraints placed on labour would cause additional indirect costs to the economy (Cochrane, 1997; Stephane Hallegatte & Przyluski, 2010; Veen, 2004). Related to the effects on the labour force is the reduction in the income of the affected workers. This in turn would represent a decrease in the final demand of the products they usually consume, which again will represent additional indirect damages owing to the reduction in the output of the industries that supply those goods (A. Z. Rose, 2004; Veen, 2004).

The appraisal of the total economic costs of a natural disaster must consider, as far as possible, all these direct and indirect damages.

2.1.2 General equilibrium costs

Some authors (Stephane Hallegatte & Przyluski, 2010; Okuyama, 2009) have pointed out the existence of other kinds of costs rarely considered in natural disaster impact analysis, which are termed as general equilibrium costs and usually become visible in the long run. One of these effects arises from the income level of countries and the loss of human capital. In the case of developing countries, the level of skills in the labour force is diverse and high-skilled labour force is limited, so if there were a considerable loss in this input, its replacement would be difficult. Other costs emerge from negative externalities associated with the psychological effects of a disaster, which would have a long-term negative impact on the productivity of the labour force. These effects are far more complex to assess and, depending on the purpose of the analysis, it may be considered insufficiently relevant to include in the economic impact analysis. For instance, it is not considered in the planning of public policies of adaptation, or for purposes of climate risk management.

Other authors (Stephane Hallegatte & Przyluski, 2010) have emphasised different outcomes in indirect costs, depending on the estimation of loss and the actions taken. Loss estimation depends in great measure on the methodology used and, in combination with the objectives of policy-makers, influence the actions to be taken.

2.2 Methodologies used in Impact Analysis

For evaluating the total economic costs of a natural disaster, the economic theory provides with several techniques. The most common ones are presented below. It should be noted that there is not a consensus yet about the superiority of one over another, and the differences in results are mainly based on the different approaches, assumptions, data, and reference theories (Greenberg et al., 2007).

2.2.1 Input-Output model

The Input-Output (IO) model was developed by Wassily Leontief, a Nobel Prize laureate economist, in the 1930s and was founded on the basic idea of the circular flow of the economy, representing the complex transactions in the economy in a transparent and simple way. Its main advantages are the possibility of managing the interconnectedness among sectors, agents and regions. Recent research on IO modelling allow the compatibility with other satellite data sources (Timmer, Dietzenbacher, Los, Stehrer, & Vries, 2015), as well as with some models from other disciplines, such as flooding simulation or GIS modelling. This is relevant in disaster impact analysis, as these engineering models can provide quick and accurate data. They also allow for estimations on projected scenarios, considering different patterns of climate change and socio-economic development (Cole, 2003; Greenberg et al., 2007; Li et al., 2013;

Miller & Blair, 2009; Okuyama, 2009; A. Z. Rose, 1995, 2004). The information in the IO tables comprises all the production inputs, and all the consumed outputs (A. Z. Rose, 1995). This information is presented in value terms but is responsive to physical changes, as one basic assumption in the standard IO is the prices rigidity (Greenberg et al., 2007; Okuyama, 2007). The production technology is implicit in the model, where the production is a linear combination of the productive factors that keep a fixed proportion assumption. These are the Leontief production function, or production function of prefect complements, where there are no possibilities of substitution between the productive factors. For the standard IO model, the productive factors are the capital and the labour (Cole, 2003; A. Z. Rose, 1995). The characteristics of the IO model make it very suitable for impact analysis, especially for the assessment of indirect losses, taking advantage of the accounting of the inter-industrial transactions all along the value chain, as well as the final consumption transactions (Cole, 2003; Okuyama, 2009; A. Z. Rose, 1995). Another advantage is that the analysis of direct and indirect damages can be disaggregated at industry sector level (Okuyama, 2009; A. Z. Rose, 2004).

However, the application of the IO model to the impact analysis has been subject to a series of criticisms. Firstly, the standard IO model is a static model, and it is based on the assumption of linear relationships among the productive factors, the product and the demand. It also presents rigidity in prices, and in input and import substitutions (Cole, 2003; Greenberg et al., 2007; Okuyama, 2007, 2009; A. Z. Rose, 2004). It is essentially a demand-driven model, which makes difficult the impact assessment from supply constraints. Additionally, the standard version does not consider changes in consumers' behaviour, and changes in productivity (Cochrane, 2004; Li et al., 2013).

Despite these rigidities, the adaptability of the model has allowed the developments that overcome most of the mentioned disadvantages, at the time of keeping the parsimony principle and transparency in the analysis (Cole, 2003; Okuyama, 2007; A. Z. Rose, 1995; Veen, 2004). This has allowed the wide use of IO-extended models in the disaster impact analysis.

2.2.2 Computable General Equilibrium models

Another methodology that has been widely used in impact analysis is the Computable General Equilibrium (CGE) model. Some researchers have claimed that this model is an improvement over some of the main constraints in the IO model. The CGE model allows for impact assessment from supply constraints. It also considers price changes, allows for a non-linear modelling, and considers the flexibility in input and import substitutions. At the same time, it maintains some of the main advantages of the IO model, such as the regional and sectoral analysis (Cochrane, 2004; Okuyama, 2007, 2009; A. Z. Rose, 2004). This is because the basis of the CGE models lies in an extension of the IO tables, the Social Accountability Matrix (SAM). These matrices retain the information and disaggregation of the inter-industrial transactions, at the time that disaggregate the information in a wider number of institutions such as households, corporate sectors and government (Greenberg et al., 2007; A. Z. Rose, 1995, 2004; Veen, 2004).

However, the CGE models have received some critiques when applied specifically to the impact assessment of natural disasters. This is because the model considers the economy to be in equilibrium following the disaster, whereas it has been argued that precisely those imbalances in the economy are one of the main characteristics of a post-disaster situation, and that these imbalances are one of the main sources of indirect damages. Additionally, the behaviour of agents is not always optimal to empty the markets in these situations, as it is assumed in CGE analysis. In a general context, the CGE model has been criticised because of the large number of parameters and the fact that some of the most relevant are user-calibrated (Cochrane, 2004; Greenberg et al., 2007; Okuyama, 2007, 2009; A. Z. Rose, 1995, 2004; Veen, 2004).

Despite these critiques, the CGE model and extensions have been widely used for the appraisal of the economic impact of natural disasters. Owing to the instant prices' changes that bring the economy into a new partial equilibrium each time step during the recovery, the CGE model estimations are usually lower than in other appraisals and have been considered as an overoptimistic assessment of damages, underestimating the indirect damages by the imbalances in the markets (Li et al., 2013; Okuyama, 2007).

2.2.3 Econometric models

Econometric models have not been very widely used in the evaluation of the economic costs of natural disasters. The main strengths of the econometric models are their rigorous statistical foundations, which make them suitable for forecasting. The time-series data used in these models allows for counterfactual analysis as well as uncertainty analysis (Cochrane, 2004; Greenberg et al., 2007; Stephane Hallegatte & Przyluski, 2010; Li et al., 2013; Okuyama, 2007, 2009).

However, the econometric models seem ill-suited for impact analysis, as the data they use usually does not contain specific information on previous disasters. Additionally, the scale of the analysis is usually at the national level, which makes regional analysis difficult (Cochrane, 2004; Greenberg et al., 2007; Li et al., 2013; Okuyama, 2007, 2009). Finally, it is difficult to distinguish between direct and indirect costs using econometric models (Okuyama, 2007, 2009).

2.2.4 Hybrid models

Hybrid models are the integration of one or more of the previous economic models and alternative models from other disciplines. In the impact assessment of natural disasters, the most common alternative models include engineering models to produce flood maps, georeferenced modelling and analysis base on GIS, and the use of the ‘damage functions’[11]. One of the most extensive hybrid models is the HAZUS model, which is based on the IO model, and incorporates engineering models with geographical information. It was made to deal effectively with supply constraints and to simulate the recovery path through time. One of its main constraints is the user-calibration of relevant parameters (Cochrane, 2004; Greenberg et al., 2007).

2.2.5 Survey-based impact analysis

Finally, some attempts at impact analysis have been made through in-place surveys after the disaster, and some of them use a cohort analysis with a series of interviews through time. The assessment through surveys captures detailed information at the individual scale, which make the analysis more accurate and provides information on some of the aspects that the statistical models cannot capture. However, the level of information and lack of representativeness make them unsuitable for a macroeconomic analysis (Cochrane, 2004). However, the information has been proved to be very useful for parameters calibration when combined with macro-economic models (Harries et al., 2015).

2.2.6 Choosing an Analytical Framework

This section exposes the choice for the modelling framework adopted in this research. It is based on the critical review of pros and cons related to the most used methodologies in the research area of economic impact assessment for natural disasters. In a general view, we can

[11] This concept will be extended later in the thesis.

say that the estimations from the IO models are usually seen as the upper-bound estimation, while estimations from CGE models are commonly taken as the lower bound or ‘optimistic’ estimation (Okuyama, 2007, 2009; A. Z. Rose, 2004). Another distinction is that the estimations from IO models are regarded as short-term costs, while estimations from CGE models can be considered as long-term costs (E. E. Koks et al., 2015). As an average solution, some authors (Stephane Hallegatte & Przyluski, 2010) have suggested the use of Hybrid (IO-CGE) models, however, they are highly demanding on data and they depend on a large number of parameters, many of which are user-calibrated (Cochrane, 1997; Okuyama, 2003).

Reviewing the use frequency of these models, some researchers (Cole, 2003; Li et al., 2013; Okuyama, 2007; A. Z. Rose, 2004) found that IO models (and the ad hoc extensions) are more widely used than the CGE models. They argue that this is mainly based on the flexibility of the IO modelling to deal with the different aspects involved in the assessment of the economic impact of a natural disaster, at the time of keeping advantages such as the parsimony principle and the transparency in the results, and the possibility of regional and industry-sectoral analysis. Among the adaptations for impact assessments, the consideration of the economy’s disequilibrium and the supply-bottlenecks; the products substitution; changes in intermediate and final demand; and the time-dynamics of the recovery stand out (Cole, 2003; Okuyama, 2007, 2009; A. Z. Rose, 2004; Veen, 2004). The research on impact analysis in IO modelling has shown great dynamism in recent years which promises further development and refinement of modelling (Okuyama, 2007, 2009; A. Z. Rose, 2004; Veen, 2004).

Owing the above reasons, this thesis bases its methodology on the IO modelling. To summarise, the main advantage of IO model that was considered to following this research path, is related with the specific characteristics that a disaster imposes on an economy. It should be remembered that CGEs models consider an economy in equilibrium all the time after the disaster, due to the flexibility of price setting mechanism. This means that IO framework accepts that the disaster imposes imbalances among the markets and the general economy’s equilibrium, and it is able for accounting those imbalances during the recovery process.

The next section expands upon the IO model rationale and extensions; and the evolution of cases study applications. The selection of reviewed models responds to the evolution of IO modelling for impact assessment. Each model extension is thoroughly reviewed and provides with wider tools than those used in this thesis, but may be implemented in the impact assessment of natural disasters. Those in section 2.3 are companied with a case study from the literature review where has been applied for impact assessment of natural disasters. That is the case for the standard IO model and the Inoperability IO model (IIM) developed by R. J. Santos (2006). Or the use of the standard IO model in the appraisal of costs by Hurricane Sandy by the Natural Hazard and the Earth System Science. In the case of the price model approach (or Gosh model), Dietzenbacher (1997) modify it to apply combine with the extraction method to assessing the economic impact of total failure in a specific industrial sector.

Sections 2.4 and 2.5 introduce the environment related IO models. These are presented due to the relevance of environment damage from natural disasters, and climate change in general. However, more research linking natural disasters and environment impact is needed.

Finally, the IRIO and the MRIO models are presented in section 2.6., which provide the modelling elements to reach the Objective 2, a multiregional flood footprint model for examining the cascading effects beyond physically impacted regions. This thesis constitutes the first attempt for assessing the economic costs of natural disasters at a multiregional scale. The previous research on this can be found in the Multiregional Inoperability IO model, whose main purpose is to show the inoperability of the economic system instead of the appraisal of costs.

The rest of the chapter depicts the exclusive IO modelling for disaster impact analysis, that comprises the work upon which this research is supported.

2.3 Input Output analysis approach[12]

This section describes the building blocks of the IO modelling and the reference framework for the methodology developed in this thesis.

The main strength of the IO model is the representation in an elegant and simple way of the complex interconnectedness and flow of goods and services among different economic agents. The model departs from the basic theory in economics of the circular flow of inputs and outputs. The information is accommodated in the IO tables, which account for the inter-industrial[13] transactions (sales and purchase), final demand, and payment for productive factors, normally depicted as the value added of the sector.

[12] All subsections in Input Output Literature Review are mostly based on Miller and Blair (2009).

[13] In what follows from the thesis, the terms 'economic sector', 'industry' or 'industrial sector' are used interchangeably.

In this section, the rationale of the IO model is described in detail. Regarding the mathematical symbols and formulae along the whole thesis, matrices are represented by bold capital letters (e.g., $\boldsymbol{X}$), vectors by bold lowercase (e.g., $\boldsymbol{x}$) and scalars by Italic lowercase (e.g., x). By default, vectors are column vectors, with row vectors obtained by transposition (e.g.$\boldsymbol{x}'$); a conversion from a vector (e.g., $\boldsymbol{x}$) to a diagonal matrix is expressed as a bold lowercase letter with a circumflex (i.e. $\hat{\boldsymbol{x}}$); the operators '.*' and './' are used to express element-by-element multiplication and the element-by-element division of two vectors, respectively.

The premise is that industries produce goods and services, some of which are purchased by other industries (z_{ij}) as inputs for production (inter-industry transactions), where the subscript i refers to the selling industry, while the subscript j refer to the purchasing industry. The rest is advocated to satisfy the final demand (f_i). Therefore, the total sales for both inter-industry and final demand represent the total *output* of the sector i (x_i). Additional to the cost of inputs for production, industries need to pay for the productive factors, such as labour and the rent of capital, which represents the value added to the production of the sector (v_i). Thus, the payment for input products and the payment for the productive factors account for the total value of the *inputs* to realise the production of sector i (the same x_i values). Thus, maintaining the basic economic theory of a circular flow, it is assumed that the economy is in equilibrium when the total value of input ($\boldsymbol{Z} + \boldsymbol{v}$) equals the total value of inputs that the economy consumes ($\boldsymbol{Z} + \boldsymbol{f}$).

The mathematical development of the IO model arranges the economic transactions into a linear algebraic model. This is a set of n linear equations (for n industries) which is determined with the same number of unknowns: the production of each of the n sectors, x_i (along the course of this thesis, it is assumed that each industry produces just one homogenous product, a widely-used assumption). The information about the economic transactions is usually disclosed in three tables (as in Figure 2.1): inter-industry transactions table ($\boldsymbol{Z}$), final demand table ($\boldsymbol{f}$) and value added table ($\mathbf{v}$). It must be noted that the information in the IO tables are expressed in value (monetary) terms, although they refer to physical quantities, as one assumption in the IO model is price rigidity.

The inter-industrial transactions table ($\boldsymbol{Z}$) contains the information of industry-to-industry trade. Row-wise, for a given sector (row) i it shows the inter-industrial sales to each other sectors, j. If the information is read column-wise, it shows the needs of sector j of inputs from each other sector, i.

The final demand table ($\boldsymbol{f}$) shows the demand of products and services for final consumption. The information is usually disaggregated in the main consumption categories (although further disaggregation is possible): household consumption, government expenditure, capital investment and the balance for external trade, or net exports (this is basically the account of exports minus imports).

Finally, the table with information about the value added contains the payment to the primary *inputs* or productive factors. The main two factors are the payment for labour and the rent for capital. Although other payments for production can be considered in this table, such as the payment of taxes. It is worth nothing that the sum of all value added equals the sum of all final demand, implying that all final consumption is purchased with the payment to the services for production.

Figure 2.1 Input Output table

	Inter-industry transactions	**Final demand**	**Total output**
	$\begin{bmatrix} z_{11} & \cdots & z_{1j} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ z_{i1} & \cdots & z_{ij} & \cdots & z_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ z_{n1} & \cdots & z_{nj} & \cdots & z_{nn} \end{bmatrix}$	$\begin{bmatrix} f_1 \\ \vdots \\ f_i \\ \vdots \\ f_n \end{bmatrix}$	$\begin{bmatrix} x_1 \\ \vdots \\ x_i \\ \vdots \\ x_n \end{bmatrix}$
Value added	$\left[va_1 + \cdots + va_j + \cdots + va_n\right]$		
Total inputs	$\left[x_1 + \cdots + x_j + \cdots + x_n\right]$		

Source: Based on Miller and Blair, 2009.

2.3.1 Standard Input Output model[14]

In this section, the basic mathematical structure of the standard IO model is introduced.

[14] We will follow the nomenclature developed in Miller and Blair (2009).

Let z_{ij} be the amount of product from industry i sold to industry *j*; and f_i the total final demand for the sector's i products. Note that the total final demand for each sector (f_i) accounts for the sum of households' consumption, government expenditure, capital investment and net exports. Then, the total production of sector i (x_i) equals the sum of all inter-industry sales of this sector to the other sectors, plus the total final demand. Thus, the distribution of product i in the economy, for all sectors, can be represented as follows.

$$
\begin{gathered}
x_1 = z_{11} + z_{12} + \cdots + z_{1j} + \cdots + z_{1n} + f_1 \\
\vdots \\
x_i = z_{i1} + z_{i2} + \cdots + z_{ij} + \cdots + z_{in} + f_i \\
\vdots \\
x_n = z_{n1} + z_{n2} + \cdots + z_{nj} + \cdots + z_{nn} + f_n
\end{gathered} \tag{2.1}
$$

In a shorter expression, the production for sector i can be expresed as:

$$
\begin{aligned}
x_i &= z_{i1} + z_{i2} + \cdots z_{ij} + \cdots + z_{in} + f_i \\
&= \sum_j z_{ij} + f_i
\end{aligned} \tag{2.2}
$$

The linear equation system can be expressed in a linear algebra equation (matrix form):

$$
\boldsymbol{x} = \boldsymbol{Zi} + \boldsymbol{f} \tag{2.3}
$$

where:

$$
\boldsymbol{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_i \\ \vdots \\ x_n \end{bmatrix}; \boldsymbol{Z} = \begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{n1} & \cdots & z_{nn} \end{bmatrix} \ and\ \boldsymbol{f} = \begin{bmatrix} f_1 \\ \vdots \\ f_i \\ \vdots \\ f_n \end{bmatrix}
$$

And $\boldsymbol{i}$ is a n-dimensional vector of one's that allows the sum of each row in $\boldsymbol{Z}$.

The linear arrangement of inter-industry transactions into the economy implicitly assumes fixed proportions between the production inputs and the production outputs. This is reflected in the technical coefficients matrix (A), whose typical element $[a_{ij}]$ reflects the proportion of product that industry j needs from industry i to produce one unit of product in the industry j. It can be noted that each column in $\boldsymbol{A}$ represents the proportions of the inputs needed by industry *j* to perform its product. This can be seen as the recipe to make each unit of product j.

The matrix of technical coefficients is obtained when each element of column j in matrix $\boldsymbol{Z}$ is divided by the product of sector j, x_j:

$$\boldsymbol{A} = \boldsymbol{Z} * \widehat{\boldsymbol{x}}^{\boldsymbol{-1}} \tag{2.4}$$

Where:

$$\widehat{\boldsymbol{x}} = \begin{bmatrix} x_1 \cdots 0 \\ \vdots \quad \ddots \quad \vdots \\ 0 \cdots x_n \end{bmatrix} \tag{2.5}$$

Thus,

$$\widehat{\boldsymbol{x}}^{\boldsymbol{-1}} = \begin{bmatrix} 1/\,x_1 & \cdots 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1/x_n \end{bmatrix} \tag{2.6}$$

And each element of the matrix is:

$$\boldsymbol{a_{ij}} = \boldsymbol{z_{ij}}/\boldsymbol{x_j} \tag{2.7}$$

Substituting the equation (2.7), equation (2.1) can be rearranged to show how each sector depends on the flow of inputs from other sectors to perform its own productions:

$$\begin{aligned} &\boldsymbol{x_1} = \boldsymbol{a_{11}x_1} + \boldsymbol{a_{12}x_2} + \cdots + \boldsymbol{a_{1j}x_j} + \cdots + \boldsymbol{a_{1n}x_n} + \boldsymbol{f_1} \\ &\vdots \\ &\boldsymbol{x_i} = \boldsymbol{a_{i1}x_1} + \boldsymbol{a_{i2}x_2} + \cdots + \boldsymbol{a_{ij}x_j} + \cdots + \boldsymbol{a_{in}x_n} + \boldsymbol{f_i} \end{aligned} \tag{2.8}$$

$$\boldsymbol{x_n} = \boldsymbol{a_{n1}x_1} + \boldsymbol{a_{n2}x_2} + \cdots + \boldsymbol{a_{nj}x_j} + \cdots + \boldsymbol{a_{nn}x_n} + \boldsymbol{f_n}$$

Let:

$$\boldsymbol{A} = \begin{bmatrix} a_{11} \cdots a_{1n} \\ \vdots \quad \ddots \quad \vdots \\ a_{n1} \cdots a_{nn} \end{bmatrix}$$

Thus, substituting equation (2.8) in equation (2.3) the linear algebraic model can be solved in the following way:

$$\begin{aligned} \boldsymbol{x} &= \boldsymbol{Ax} + \boldsymbol{f} \\ (\boldsymbol{I} - \boldsymbol{A})\boldsymbol{x} &= \boldsymbol{f} \\ \boldsymbol{x} &= (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{f} \\ \boldsymbol{x} &= \boldsymbol{Lf} \end{aligned} \tag{2.9}$$

Where $\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1}$ is known as the Leontief or total requirement matrix and each element $[l_{ij}]$ represents the total change in x_i attributable to the change of one unit in final demand, f_j. So, the expression on equation (2.9) denotes the dependency of changes in production from changes in final demand, which makes the IO model a demand-driven model.

For impact analysis purposes, it is often used the appraisal of changes on final demand, as differences between an initial and final value, in total production, $\boldsymbol{x}$. Changes in $\boldsymbol{f}$ can be expressed as $\Delta\boldsymbol{f} = f^1 - f^0$, where the superscript 1 is for final value and 0 for the initial one. Then, we can express the changes on production from changes on final demand as:

$$\boldsymbol{\Delta x} = \boldsymbol{L\Delta f} \tag{2.10}$$

2.3.2 Applications to impact assessment of natural disasters

Due to the characteristics of natural disasters and the needs for extensions in the modelling to overcome some of the original rigidities in the standard IO model and make it suitable for impact assessment, it is rare to find direct applications of the standard IO model for estimation of the economic losses from a disaster. Nevertheless, when there exists the necessity of having prompt answers to formulate a general assessment of the damage, particularly in specific cases where a sectoral radiography of the economy after a disaster is needed, the standard IO model becomes a useful tool. This was the case after Hurricane Sandy affected the west coast of North America. To make a prompt estimation of indirect losses (to help in the planning of recovery strategies), the Natural Hazard and Earth System Science (NHESS) carried out an analysis of damages on different sectors of the US economy using a standard IO model. Most of the damages were felt on the chemical and textile industries. The analysis assumed an average disruption (power shortage) of two days on average which affected around 26.5 % of manufacturing sectors. This analysis was made to assess the effects of disruptions in what can be considered critical infrastructure (i.e. that on which many sectors depend). They estimated the indirect damages as US $ 9.4 billion (Kunz, 2013).

Another application of the standard IO model was in the development of the Inoperability Input-Output model (IIM) developed by R. J. Santos (2006). In the IIM, the *inoperability* is defined as the difference between the planed output of the economy and the level of output that the system is able to provide after a negative shock. Based on this concept, the IIM assumes a direct relation between the value of transactions and the interdependency between economic sectors. Then, the matrix of technical coefficients ($\boldsymbol{A}$) becomes a matrix where the coefficients represent the strength of the relationships between sectors ($\boldsymbol{A}^*$) where each element $[a_{ij}^*]$ indicates the inoperability in sector i attributable to disruptions in sector j. It must be noted that the original IIM is a demand-driven and static model where the equilibrium is assumed at each step (J. R. Santos & Haimes, 2004). Despite its criticised rigidities, the IIM has proved useful in assessing the inoperability among economic sectors, which has assisted in preparing or mitigating adverse impacts from negative shocks, by identifying the most vulnerable sectors (Crowther et al., 2007).

2.3.3 Leontief Price Model based on Monetary Values

In the original version, the IO model was meant to measure the transactions in physical units. However, it is the usual case that transactions are expressed in monetary or value terms, and no prices nor quantities are disclosed.

From the structure of the basic IO model (see equation(2.11)) the information in the j-*th* column (sector) discloses the value of all purchased products used as inputs, plus the value of payment to production services (i.e. payment for labour, capital, taxes). The sum of all these inputs equals the value of production of sector *j* (the same as the value of all output for the same sector). This is:

$$x_j = \sum_i z_{ij} + v_j \tag{2.11}$$

Or in a matrix form:

$$\boldsymbol{x}' = \boldsymbol{i}'\boldsymbol{Z} + \boldsymbol{v}' \tag{2.12}$$

Where $\boldsymbol{i}'$and $\boldsymbol{v}'$ are row vectors, and the last represent the sum of the value added for each sector *j*.

From equation (2.4) we have that:

$$\boldsymbol{Z} = \boldsymbol{A}\hat{\boldsymbol{x}} \tag{2.13}$$

Substituting in equation (2.12):

$$\boldsymbol{x}' = \boldsymbol{i}'\boldsymbol{A}\hat{\boldsymbol{x}} + \boldsymbol{v}' \tag{2.14}$$

Then, post-multiplying this last expression by $\hat{\boldsymbol{x}}^{-1}$ provides a normalization of values on the right side of the equation, so we obtain:

$$\boldsymbol{i}' = \boldsymbol{i}'\boldsymbol{A} + \boldsymbol{v_c}' \tag{2.15}$$

Where $\boldsymbol{v}_c' = \boldsymbol{v}'\hat{\boldsymbol{x}}^{-1}$. The last equation shows the total cost of production for one unit of production in each sector, which can be though as the cost to produce \$1 of value of product in each sector. In this Leontief *Price Model,* the left side of the equation represents the base year price indexes and is denoted by $\widetilde{\boldsymbol{p}}'$. Substituting this in equation (2.15) we obtain the form of the price model:

$$\widetilde{\boldsymbol{p}}' = \widetilde{\boldsymbol{p}}'\boldsymbol{A} + \boldsymbol{v_c}' \tag{2.16}$$

And following an analogous development of the equation to let indexes prices as dependent variables we have:

$$\widetilde{\boldsymbol{p}}' = \boldsymbol{v_c}'\boldsymbol{L} \tag{2.17}$$

The last expression discloses the dependency of prices' changes from changes in any of the components of the value added.

2.3.4 Leontief Price Model based on physical data

Let s_{ij} be the physical quantity of product that industry j buys to industry i and d_i the physical consumption of final demand for each i industry. Finally, let q_i be the total production of industry i in physical terms. So, analogously with the standard IO model, we can represent the interindustry relations in physical terms as:

$$\boldsymbol{q_i} = \boldsymbol{s_{i1}} + \boldsymbol{s_{i2}} + \cdots \boldsymbol{s_{ij}} + \cdots + \ \boldsymbol{s_{in}} + \boldsymbol{d_i} \tag{2.18}$$

and in matrix notation:

$$\boldsymbol{q} = \boldsymbol{Si} + \boldsymbol{d} \tag{2.19}$$

Also in a parallel way, the technical coefficients (in physical) terms are:

$$c_{ij} = \frac{s_{ij}}{q_j} \tag{2.20}$$

and in matrix form:

$$\boldsymbol{C} = \boldsymbol{S}\widehat{\boldsymbol{q}}^{-1} \tag{2.21}$$

To let the production as a dependent variable of changes in final demand, the same process as in equation (2.9) is followed to obtain:

$$\boldsymbol{q} = (\boldsymbol{I} - \boldsymbol{C})^{-1}\boldsymbol{d} \tag{2.22}$$

This is the correspondent model in physical units related to the standard IO model expressed in value terms. The corresponding approximation to the model in monetary terms is made with the introduction of prices. Assume that prices for the product of each sector are known (p_i), as well as for labour price[15] (or wage) (p_{n+1}). Note that the labour price (or wage) is considered homogenous among the different sectors. Then, the value of each element from the physical IO model is obtained just multiplying them for their correspondent price:

$$x_i = p_i q_i$$
$$z_{ij} = p_i s_{ij}$$
$$f_i = p_i d_i$$

And from equation (2.2) we get the original IO model in value terms:

$$\begin{aligned} x_i &= \sum_j p_i s_{ij} + p_i d_i \\ &= \sum_j z_{ij} + f_i \end{aligned} \tag{2.23}$$

And in matrix form:

$$\boldsymbol{x} = \boldsymbol{Zi} + \boldsymbol{f} \tag{2.24}$$

[15] For simplicity, it is assumed that all value added depends only on labour payment.

Once we have transformed the standard IO model into value terms, the next step is to combine it with the above price model. Assuming a general wage rate for all sectors (p_{n+1}), we can obtain the total cost on labour for each sector ($p_{n+1}s_{n+1,j} = v_j$); and substituting this in equation (2.11) we get:

$$p_j q_j = \sum_i p_i s_{ij} + p_{n+1}s_{n+1,j} \tag{2.25}$$

Where $s_{n+1,j}$ is the primary input (labour) to produce one unit of q_j. And dividing all by q_j, we obtain:

$$\begin{aligned} p_j &= \sum_i p_i s_{ij}/q_j + p_{n+1}s_{n+1,j}/q_j \\ &= \sum_i p_i c_{ij} + p_{n+1}c_{n+1,j} \end{aligned} \tag{2.26}$$

Or in matrix form:

$$\boldsymbol{p}' = \boldsymbol{p}'\boldsymbol{C} + \boldsymbol{v_c}' \tag{2.27}$$

Where $\boldsymbol{v_c}'$ is a row-vector which expresses the labour cost for unit of physical product, for each industry j. Similar to the equation (2.16), the last equation tells us that the price of the product in each industry is equal to the cost of inter-industry inputs plus the cost of production services (value added). As previously shown, the changes in prices can be expressed in terms of changes in the value of primary inputs (as labour). This is the Leontief price model based on physical units:

$$\boldsymbol{p}' = \boldsymbol{v}(\boldsymbol{I} - \boldsymbol{C})^{-\boldsymbol{1}} \tag{2.28}$$

This model is a less restrictive version of the IO model regarding prices' changes. However, it presents an important disadvantage, which is that the physical relations for production remain fixed.

2.3.5 Supply IO model. The Ghosh Model

From the development of the demand-driven model, Gosh (1958) proposed an alternative model to relate the production of each sector with the supply of primary inputs, such as labour force. Mathematically, the model proposes to divide the elements in row i by the correspondent sectoral gross product j, instead of each element in a column j by the sectoral gross product (x_i). This process generates the matrix $\boldsymbol{B}$:

$$\boldsymbol{B} = \hat{\boldsymbol{x}}^{-1}\boldsymbol{Z} \tag{2.29}$$

Each element of matrix $\boldsymbol{B}$**,** $[b_{ij}]$, are usually referred as *allocation* coefficients, as they express the proportion of sales of sector i to all industries j. From the above expression, and given the fact that $\boldsymbol{x}' = \boldsymbol{i}'\boldsymbol{Z} + \boldsymbol{v}'$, we can obtain an expression where the production of each sector becomes a function of the primary inputs. The process is analogous as the one to obtain the *input inverse* (Leontief Inverse Matrix):

$$\begin{aligned} \boldsymbol{x}' &= \boldsymbol{i}'\hat{\boldsymbol{x}}\boldsymbol{B} + \boldsymbol{v}' \\ &= \boldsymbol{x}'\boldsymbol{B} + \boldsymbol{v}' \\ &= \boldsymbol{v}'(\boldsymbol{I} - \boldsymbol{B})^{-1} \\ &= \boldsymbol{v}'\boldsymbol{G} \end{aligned} \tag{2.30}$$

Where $\boldsymbol{G}$ is named as the *output inverse* matrix, and whose elements $[g_{ij}]$ represent the total change in the value of output in sector j from a change of one unit in the availability of the *primary inputs* from sector i. As previously, we can show the relation in changes in the next expression:

$$\boldsymbol{\Delta} x' = (\boldsymbol{\Delta} v')G \tag{2.31}$$

Parallel to the interpretation of columns and rows sums in the quantity model (the Leontief model), the row sum in the Ghosh model can be thought as the *input multipliers* that show the effect on total output in the economy as a change in one-unit of value in the supply of primary inputs from sector i. In an analogue way, the column sum of elements in $\boldsymbol{G}$ gives the total effect on the output of a sector j from the change of one-unit value in the supply of primary factors in each industry. It can be noted that the information provided from the *input multipliers* can be applied for the best allocation of additional primary inputs among the economic sectors, to maximise the increase of output in the economy (the opposite is also true, about the potential reduction in output from shortages in primary inputs). These *input multipliers* can, then, be interpreted as *forward linkages* from one sector to the rest of the economy along the value chain. In other words, it is the effect that the change in primary inputs in one sector causes in the output of all other sectors in the economy.

Nevertheless, there is a problem with the above interpretation and the concept of fixed proportions in productive factors (which is implicit on the core of the IO model). From equation (2.14), it is stated that a change in primary inputs from industry i ($\Delta\boldsymbol{v}' = [0, \dots, \Delta v_j, \dots, 0]$) will produce a change in the output of all other linked industries within the economy ($\Delta\boldsymbol{x} = [\Delta x1, \dots, \Delta x_i, \dots, \Delta x_n]$), but without a change in primary inputs of those sectors; which is in contradiction with the production function of perfect complements (or Leontief Production Function).

2.3.6 Reinterpretation as a price model

To overcome this contradiction, Erik Dietzenbacher (1997) proposed to interpret the original Ghosh model as a *price* model instead of a *quantity* one. This is, instead of $\Delta\boldsymbol{v}'$ meaning a change in quantities of primary inputs, this now represents the change in value or costs of those primary inputs with an effect in changing the values of output in other sectors. Because the quantities remain fixed under this interpretation, the change in value is through changes in prices. This means that changes in the price of primary inputs will affect the price of products in other industries. This is straightforward from the fact that $x_j = p_j q_j$.

If

$$\boldsymbol{\Delta v_i = v_i{}^1 - v_i{}^0} \tag{2.32}$$

Lead a change in x_j from its initial value:

$$\boldsymbol{\Delta x_j = x_j{}^1 - x_j{}^0} \tag{2.33}$$

Then, because quantities are assumed to be fixed:

$$\begin{aligned} \boldsymbol{\Delta x_j} &= \boldsymbol{p_j^1 q_j^0 - p_j^0 q_j^0} \\ &= (\boldsymbol{p_j^1 - p_j^0})\boldsymbol{q_j^0} \\ &= (\boldsymbol{\Delta p_j})\boldsymbol{q_j^0} \end{aligned} \tag{2.34}$$

Which clearly shows that the effect of a change in primary inputs of sector i is going to affect only the prices in the output of sector j. As can be noted, this result is the same as the one obtained in the Leontief price model (see equation (2.27)), reason for which this model can be thought (as in the former) as *cost-push* input-output model.

2.3.6.1 Applications in natural disasters

In natural disasters (as well as in man-made disasters), it has been argued that most disruptions come from the supply side of the production chain. To model the disruptions from the supply side, the concepts of the supply IO model have been extended in the Inoperability Input Output Model (IIM). As mentioned previously, the original IIM was a demand-driven model. Later, Leung, Haimes, and Santos (2007) extended the model to the supply-side price IIM to consider the consequences of supply disruptions in a disaster aftermath. As discussed earlier in this section, the supply IO model considers changes in prices when changes in value added occur. This is because changes in quantities from changes in value added (changes in supply side) have never been totally accepted, so that the model is considered as a price-change model. Nevertheless, cascading effects can be measured as the changes in final demand from price changes on the supply side. The transmission mechanism is modelled through the price-demand elasticity concept, which measures the percentage change in physical demand of a product associated with percentage changes in its price.

A further dynamic extension of the IIM, using the supply-price model, was developed by Xu, Hong, He, Wang, and Chen (2011) in the Supply-Driven Dynamic Inoperability Input-Output Price Model (SDIIM). Park (2009) uses the Dietzenbacher reinterpretation of the Ghosh Model as a sensitivity-price model when assessing the impacts in the US economy after Hurricanes

Katrina and Rita, considering the changes in prices of the oil industry. He argues that in the short-term, the inter-industrial structure of the economy remains unchanged and changes in agents' behaviour to reach the equilibrium are realised through price changes. As in Leung et al. (2007), he uses the price elasticities to characterise changes in quantities from disruptions in prices of the oil-refinery sector.

2.3.7 Backward and forward linkages

The manageability of inter-industrial links in IO modelling allows the assessment of the relative importance of one sector within the economy. The purpose of the analysis of backward and forward linkages is to assess the degree in which other industries are affected from a change in the production of one sector. As it has been seen, these repercussions can be run in two directions, forwards in the supply chain when the changing sector is considered as a supplier; or backwards in the demand when the sector is considered as a purchaser. The relative magnitudes of the linkages are useful to identify the *key* sectors in the economy, as they provide information of their relative importance to the performance of the entire economy.

2.3.8 Backward linkages

As a purchaser, changes in a sector's demand will affect the demand of other sectors that provide them with intermediate inputs. These changes in demand for the supplying sectors will change their production. The inter-industry linkages running in this direction are known as *backward linkages.*

Since *backward linkages* are transmitted to suppliers, one way to assess the importance of these linkages is measuring the share of supplies from other sectors related with the production in industry j. Considering what we have learnt from the IO model, we can find a straightforward reference to these shares in the *direct input coefficients* (the elements of matrix $\boldsymbol{A}$). Considering the column sum of elements in column j in the $\boldsymbol{A}$ matrix, we will obtain a measure of the *direct backward linkages* ($\boldsymbol{BL}(d)_j$) of sector j with the rest of the economy:

$$\boldsymbol{BL}(\boldsymbol{d})_{\boldsymbol{j}} = \sum_{\boldsymbol{i}} \boldsymbol{a}_{\boldsymbol{ij}} \tag{2.35}$$

Defining $\boldsymbol{b}(d) = [\boldsymbol{BL}(d)_1, \dots, \boldsymbol{BL}(d)_j, \dots, \boldsymbol{BL}(d)_n]$, the expression for all sectors can be expressed as:

$$\boldsymbol{b}(\boldsymbol{d}) = \boldsymbol{i}'\boldsymbol{A} \tag{2.36}$$

One can imagine that, since elements in $\boldsymbol{L}$ matrix represent *total requirements* coefficients, a measure of direct and indirect, or total, *backward linkages* ($\boldsymbol{BL}(t)_j$) can be analogously inferred. Following a parallel development for *direct backward linkages* we get, for each sector, the total backward linkages ($BL(\boldsymbol{t})_{\boldsymbol{j}}$):

$$BL(\boldsymbol{t})_{\boldsymbol{j}} = \sum_i l_{ij} \tag{2.37}$$

And in matrix form for all sectors:

$$\boldsymbol{b}(\boldsymbol{t}) = \boldsymbol{i}'\boldsymbol{L} \tag{2.38}$$

Where $\boldsymbol{b}(t) = [\boldsymbol{BL}(t)_1, \dots, \boldsymbol{BL}(t)_j, \dots, \boldsymbol{BL}(t)_n]$ is the vector of total *backward linkages*.

More complex measures of *backward linkages* have been developed. For instance, dividing the direct backward linkages in each sector j by the average of all linkages we obtain a normalized measure of these ($\overline{\boldsymbol{BL}}(d)_j$):

$$\begin{aligned} \overline{BL}(\boldsymbol{d})_{\boldsymbol{j}} &= \frac{BL(\boldsymbol{d})_{\boldsymbol{j}}}{\left(\frac{1}{n}\right)\sum_{\boldsymbol{j}} BL(\boldsymbol{d})_{\boldsymbol{j}}} \\ &= \frac{\sum_i a_{ij}}{\left(\frac{1}{n}\right)\sum_{\boldsymbol{i}}\sum_{\boldsymbol{j}} a_{ij}} \end{aligned} \tag{2.39}$$

Or in matrix form:

$$\bar{\boldsymbol{b}}(\boldsymbol{d}) = \frac{\boldsymbol{i}'\boldsymbol{A}}{\left(\frac{\boldsymbol{1}}{n}\right)\boldsymbol{i}'\boldsymbol{A}\boldsymbol{i}} = \frac{n\boldsymbol{i}'\boldsymbol{A}}{\boldsymbol{i}'\boldsymbol{A}\boldsymbol{i}} \tag{2.40}$$

As a normalized index, values above 1 indicate 'stronger' than average *backward linkages*, and the opposite for values below one. Certainly, this is also applicable to *total backward linkages* to obtain the *Index of Power dispersion* by Rasmussen, which results in the following expression:

$$\bar{\boldsymbol{b}}(\boldsymbol{t}) = \frac{n\boldsymbol{i}'\boldsymbol{L}}{\boldsymbol{i}'\boldsymbol{L}\boldsymbol{i}} \tag{2.41}$$

2.3.9 Forward linkages

In the case where a sector is seen as an inter-industry supplier of other sectors, changes in production of sector i will result in changes of inputs' availability for other sectors. When relations between sectors run in this direction, they are referred as *forward linkages*.

Since these linkages run in the direction of the supply chain, it became agreed to use the Ghosh model to measure them. In this context, row sums of $\boldsymbol{B}$ matrix are used to represent the proportion of the usage of sector's i products as inputs for other sectors. Analogously with *backward linkages,* the use of $\boldsymbol{G}$ matrix provides a measure of *total forward linkages*. Then, for *direct forward linkages,* we have:

$$FL(\boldsymbol{d})_{\boldsymbol{i}} = \sum_{\boldsymbol{j}} b_{ij} \tag{2.42}$$

And in matrix form:

$$\boldsymbol{f}(\boldsymbol{d}) = \boldsymbol{B}\boldsymbol{i} \tag{2.43}$$

Where $\boldsymbol{f}(d) = [\boldsymbol{FL}(d)_1, \ldots, \boldsymbol{FL}(d)_i, \ldots, \boldsymbol{FL}(d)_n]$. For *total forward linkages,* we have:

$$FL(t)_i = \sum_j g_{ij} \tag{2.44}$$

And in matrix form:

$$\boldsymbol{f}(\boldsymbol{t}) = \boldsymbol{G}\boldsymbol{i}' \tag{2.45}$$

Where $\boldsymbol{f}(t) = [\boldsymbol{FL}(t)_1, \dots, \boldsymbol{FL}(t)_i, \dots, \boldsymbol{FL}(t)_n]$.

The normalized versions of *forward linkages* are, for direct linkages:

$$\overline{FL}(\boldsymbol{d})_{\boldsymbol{i}} = \frac{FL(\boldsymbol{d})_{\boldsymbol{i}}}{\left(\frac{1}{n}\right)\sum_{\boldsymbol{i}} FL(\boldsymbol{d})_{\boldsymbol{i}}} \tag{2.46}$$

Or, in matrix form:

$$\bar{\boldsymbol{f}}(\boldsymbol{d}) = \frac{n\boldsymbol{B}\boldsymbol{i}}{\boldsymbol{i}'\boldsymbol{B}\boldsymbol{i}} \tag{2.47}$$

And for total linkages, we have the following expression:

$$\bar{f}(\boldsymbol{t}) = \frac{n\boldsymbol{G}\boldsymbol{i}}{\boldsymbol{i}'\boldsymbol{G}\boldsymbol{i}} \tag{2.48}$$

Again, values greater than one indicate ‘stronger’ than average *forward linkages*, while ‘weaker’ linkages below the unity.

2.3.10 ‘Net’ backward linkages

There is an additional approach for considering linkages in backward direction. Once it has been established that *backward linkages* can be inferred from output coefficients (elements of $\boldsymbol{L}$ matrix), it is possible to get a measurement of the relevance of a sector into the economy.

The general idea is to have a relative measure of the economic gains generated from changes in demand in sector j, regarding with the change in production in sector j that could be generated for changes in demand in other sectors.

As we will see in the appraisal of 'net' backward linkage ($\left(\boldsymbol{i}'\boldsymbol{L}\hat{\boldsymbol{f}}_c\right)_j$), when the index is bigger than one in sector j, it means that the increase in one unite of sector's j demand, will generate a more than proportional increase in the economy's product (due *backward linkages*). In the case of a key sector, this increment would be bigger than the increase in sector's j product, generated by one unit of extra demand in all its suppliers.

Let us start with a measure of the output generated in a sector i (x_i) from the final demand of sector j (f_j). This information is settled in matrix $\boldsymbol{L}\hat{\boldsymbol{f}}$. The row sum of this matrix (elements of the vector $\boldsymbol{L}\hat{\boldsymbol{f}}\boldsymbol{i} = \boldsymbol{L}\boldsymbol{f}$) is the total output in each sector generated for the final demand vector ($x_j = \sum_i l_{ij} f_i$); while the column sum (elements of the vector $\boldsymbol{i}'\boldsymbol{L}\hat{\boldsymbol{f}}$) represents the needed production in each sector to meet the final demand of sector j, ($\sum_j l_{ij} f_i$). The element-by-element ratio of the latter vector by the former vector constitutes the 'net' backward linkage of sector j. This is:

$$\begin{aligned} \boldsymbol{i}'\boldsymbol{L}\hat{\boldsymbol{f}}_{\boldsymbol{c}} &= \boldsymbol{i}'\boldsymbol{L}\hat{\boldsymbol{f}}\hat{\boldsymbol{x}}^{-\mathbf{1}} \\ &= (\boldsymbol{i}'\boldsymbol{L}\hat{\boldsymbol{f}})\left(\boldsymbol{L}\hat{\boldsymbol{f}}\boldsymbol{i}\right)^{-\mathbf{1}} \end{aligned} \tag{2.49}$$

Where each element of this row-vector is the 'net' backward linkage of each sector j (when sector i is the same as sector j), as expressed bellow:

$$\left(i'L\hat{f}_c\right)_j = \frac{\sum_j l_{ij} f_i}{\sum_i l_{ij} f_i} \tag{2.50}$$

2.3.10.1 Key sectors

Using backward and forward linkages, a usual classification of sectors is made based on the normalized indexes, where a sector is considered *key sector* if both, the normalized-backward and the normalized-forward linkages are bigger than one. In the opposite case, the sector is considered *generally independent*. When the *forward linkage* in a sector is bigger than one and the *backward* linkage is less than one, the sector is considered as demand-dependent of the inter-industry trade. If the opposite occurs, that sector would depend on the inter-industry supply.

2.3.11 Hypothetical Extraction

One last approach to measure the importance of a sector in the economy has been created. The experiment is to figure out what would be the performance of the economy in the counterfactual situation when sector j is missing.

2.3.11.1 Backward effects of hypothetical extraction

As established before, the proportions of demanded inputs by sector j are disclosed in the j-th column of matrix $\boldsymbol{A}$. So, removing this (or replacing it with a column of zeros) and following the conventional way to obtain the level of production ($\boldsymbol{x}$) from final demand ($\boldsymbol{f}$), we would find the product in the hypothetical case where sector j do not demand inputs from other sectors. Let $\overline{\boldsymbol{A}}_{(cj)}$ be the technical coefficient matrix without column j; then $\overline{\boldsymbol{x}}_{(cj)} = \left(\boldsymbol{I} - \overline{\boldsymbol{A}}_{(cj)}\right)^{\boldsymbol{-1}}\boldsymbol{f}$. It should be noted that the Leontief matrix can still be obtained, even though the new $\overline{\boldsymbol{A}}_{cj}$ has a dependent row (the zeros row), as the $(\boldsymbol{I} - \overline{\boldsymbol{A}}_{cj})$ is still non-singular due its $j^{th}j^{th}$ element is $1 \neq 0$.

Calculating the difference of this production level with the original one, and normalizing, we obtain a measure of the backward linkages of sector j. This is:

$$\mathbf{100} * \left(x - \bar{x}_{(\boldsymbol{cj})}\right)\hat{x}^{-1} \tag{2.51}$$

Where each element of this column vector ($\left(x_i - \bar{x}_{(cj)i}\right)/x_j$) represents the proportion in which sector i depends on sector j. The corresponding aggregated backward-relevance of sector i in the economy is found as $\boldsymbol{i'x} - \boldsymbol{i'}\overline{\boldsymbol{x}}_{(cj)}$**,** which is the total change in production.

2.3.11.2 Forward linkages from hypothetical extraction

The way to find the impact of the hypothetical absence of sector j as an inter-industry supplier is analogous, but unlike the *forward linkages*, this is made by subtracting the j-th row of $\boldsymbol{B}$ matrix. If $\overline{\boldsymbol{B}}_{(rj)}$ is the resulting matrix, then:

$$\overline{\boldsymbol{x}}'_{(\boldsymbol{rj})} = \boldsymbol{v}'\left(\boldsymbol{I} - \overline{\boldsymbol{B}}_{(\boldsymbol{rj})}\right)^{-\mathbf{1}} \tag{2.52}$$

Assuming that sector j does not provide inputs to other industries. Then, the aggregated impact from *forward linkages* in production of sector j is:

$$\boldsymbol{x}'\boldsymbol{i} - \overline{\boldsymbol{x}}'_{(\boldsymbol{rj})}\boldsymbol{i} \tag{2.53}$$

And in a disaggregated form

$$\left(\boldsymbol{x_i} - \overline{\boldsymbol{x}}_{(\boldsymbol{rj})\boldsymbol{i}}\right)/\boldsymbol{x_j} \tag{2.54}$$

This represents the dependency of sector i on supplies from sector j.

From this consideration of backward linkages and forward linkages, a total sectoral impact of industry j in the total production of the economy can be figured out. This is achieved by subtracting (or replacing by ceros) the column and row of the correspondent j-th sector in matrix $\boldsymbol{A}$. And, in this case, also the j-th value of final demand vector ($\boldsymbol{f}$). Those are expressed as $\overline{\boldsymbol{A}}_{(j)}$ and $\overline{\boldsymbol{f}}_{(j)}$, respectively. The 'new' product is $\overline{\boldsymbol{x}}_{(j)}$. As in the previous assessment of sectors' importance, the total change in the production caused by the absence of sector j, accounts for its importance. This has been related as a *total linkage* measure, and can be expressed in absolute terms of changes in production: $T_j = \boldsymbol{i}'\boldsymbol{x} - \boldsymbol{i}'\overline{\boldsymbol{x}}_{(j)}$. Or as percentage changes: $\bar{T}_j = 100 * (\boldsymbol{i}'\boldsymbol{x} - \boldsymbol{i}'\overline{\boldsymbol{x}}_{(j)})/\boldsymbol{i}'\boldsymbol{x}$.

2.3.12 Applications in natural disasters

Disaster impact analysis aims to account for the total impacts of the shock. As previously stated in this section, net linkages (or net multipliers) account for the total (direct and indirect) effects on the output from changes in input-supply or final demand. The Regional Input-Output Multiplier System (RIMS II) produces the net-output multipliers for the US economy and sub-regions, which considers the backward linkages and has been extensively applied to natural disasters impact analysis. An example can be found in J. R. Santos and Haimes (2004), where a reduction in output of the air-transportation sector is simulated after the attack on the World

Trade Centre in 2001. According to the authors, the impact analysis shows the more vulnerable sectors in terms of inoperability, as well as possible effects on total output. Nevertheless, they recognise that backward multipliers tend to overestimate the impact due to the rigidities in the basic model.

Veen and Logtmeijer (2003) are interested in estimating the indirect impacts of major floods in The Netherlands, using forward and backward linkages as a measure of flow disruptions in production after a dyke breakage. They make a comparison between standard IO multipliers and other multipliers adjusted to different scenarios. When relaxing some of the IO assumptions, mainly regarding flexibility in input and imports substitutions, the estimation of the indirect effects decreases; while when considering bottlenecks in a post-disaster situation, the losses are exacerbated.

2.4 Environmental Input Output modelling

The IO analysis permits to take into consideration the flow of other variables that can be associated with economic activity (e.g. energy, employment, pollution, etc.). Since pollution is intrinsically linked to production and consumption, extensions in the IO model have been made since the 1960s to deal with these concerns. The standard environmental IO analysis incorporates the flows of pollutants that result from production process as well as pollutants related with final consumption (or final demand).

From the standard IO model, which is a demand-driven model, it is possible to estimate the changes in output following a change in final demand, due to the inter-industry linkages. The environmental IO modelling considers a linear relationship (or a fixed ratio) between the amount of pollutant k associated to the production of sector j (p_{kj}), based on the current technology; and the production of that sector ($d_{kj}^{p} = p_{kj}/x_j$). This ratio provides with a technical coefficient of the emission of pollutant k that is released due to the production of one unit of product in sector i. The environmental analysis, as the analysis of changes in the release of a pollutant, can be directly derived from changes in final demand. It is notorious that measuring units in pollutants does not represent a constraint, since they are presented as fixed relations with sectoral production.

Let $\boldsymbol{D}^p = [d_{kj}^{p}]$ be the matrix of pollution output, and $\boldsymbol{x}^{p*} = \boldsymbol{D}^p\boldsymbol{x}$ be the vector of *total impacts* of each pollutant k associated to the total production of the economy; and owing to $\boldsymbol{x} = \boldsymbol{Lf}$**,** then,

$\boldsymbol{x}^{p*} = (\boldsymbol{D}^p\boldsymbol{L})\boldsymbol{f}$. Since elements in $\boldsymbol{L}$ matrix are the total impact coefficients in output of sector j from a change in final demand of sector i, the coefficients in $\boldsymbol{D}^p\boldsymbol{L}$ matrix represent the total environmental impacts. A conventional development for environmental impact assessment suggests expanding the general framework of IO model with the pollution information. So that $\widetilde{\boldsymbol{x}} = \begin{bmatrix} \boldsymbol{x}^{p*} \\ \boldsymbol{f} \end{bmatrix}$ is the expanded vector of final impacts; and $\boldsymbol{G} = \begin{bmatrix} \boldsymbol{D}^p \\ (\boldsymbol{I} - \boldsymbol{A}) \end{bmatrix}$ is the expanded direct-impact coefficients. Then:

$$\begin{aligned} \boldsymbol{G}\boldsymbol{x} &= \begin{bmatrix} \boldsymbol{D}^p \\ (\boldsymbol{I} - \boldsymbol{A}) \end{bmatrix} \boldsymbol{x} \\ &= \begin{bmatrix} \boldsymbol{D}^p\boldsymbol{x} \\ (\boldsymbol{I} - \boldsymbol{A})\boldsymbol{x} \end{bmatrix} \\ &= \begin{bmatrix} \boldsymbol{x}^{p*} \\ \boldsymbol{f} \end{bmatrix} \\ &= \widetilde{\boldsymbol{x}} \end{aligned} \tag{2.55}$$

For impact analysis purposes, it is useful to obtain a vector of the total impact in pollution and production ($\overline{\boldsymbol{x}}$), as functions of final demand. Defining $\boldsymbol{D}^{p*} = \boldsymbol{D}^p\boldsymbol{L}$ as the pollution associated to the level of production $\boldsymbol{x}$, and $\boldsymbol{H} = \begin{bmatrix} \boldsymbol{D}^{p*} \\ \boldsymbol{L} \end{bmatrix}$, it follows that:

$$\begin{aligned} \overline{\boldsymbol{x}} &= \begin{bmatrix} \boldsymbol{x}^{p*} \\ \boldsymbol{x} \end{bmatrix} \\ &= \begin{bmatrix} \boldsymbol{D}^{p*} \\ \boldsymbol{L} \end{bmatrix} \boldsymbol{f} \\ &= \boldsymbol{H}\boldsymbol{f} \end{aligned} \tag{2.56}$$

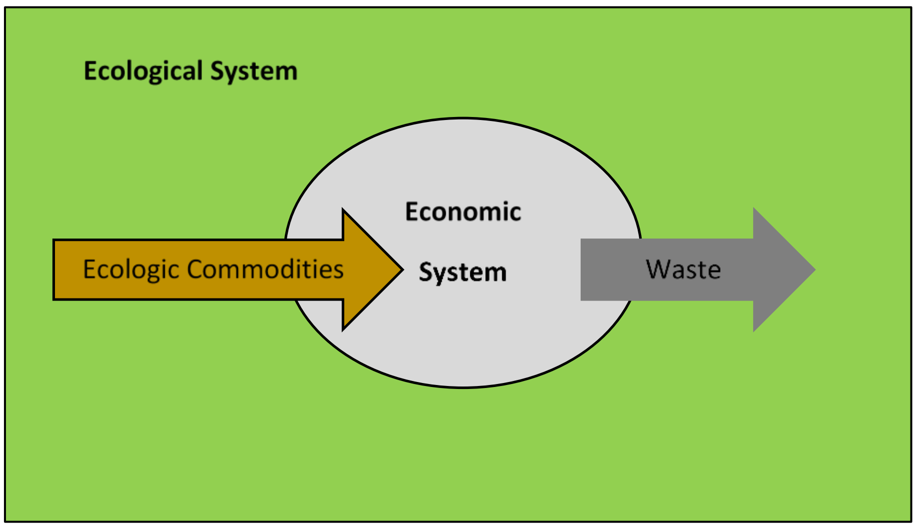
This expression results are particularly useful to assess the impact, not only in production, but also in pollution from a change in final demand vector. As usually, it can be represented in terms of variations:

$$\Delta\overline{\boldsymbol{x}} = \boldsymbol{H}\Delta\boldsymbol{f} \tag{2.57}$$

2.5 Economic-Ecological IO model

In an ecological approach, the economic system constitutes a subsystem that takes resources from the surrounding ecosystem, processes them for its functioning (production and consumption), and discards waste products to the ecological system (see Figure 2.2). If the resources that the economy takes from the environment are defined as necessary commodity-inputs for the production process (e.g. water, energy, land), it is possible to incorporate them in the IO methodology by creating a sub-matrix that relates the interactions between ecological commodities usage, and the industrial production process.

Figure 2.2 **Economic-Ecological Dynamics**



Source: Based on Tukker et al. (2008).

In the first version developed in 1968 by Herman Daly, the industrial process of the model was considered under an industry-by-industry approach; while the ecological commodities included plants, animals and even chemical reactions in the atmosphere. Nevertheless, the waste generation from the economic system to the ecological system implied the generation of a secondary commodity (the pollutant), which is in contradiction with the assumption that each industry produces only one product. To deal with this issue, Walter Isard, among others, incorporated the analysis under the commodity-by-industry approach. Since these two approaches considered the inter- and intra-relations among both ecological and economic systems, the information requirements were of such magnitude that its implementation was virtually impossible.

For practical purposes, Peter Victor considered just the entering ecological commodities into the economic process, and the residuals that return to the environment. Let us start with the representation of the commodity-by-industry economic subsystem, and consider that there are m commodities and n industries. Let $\boldsymbol{U} = [u_{ij}]$ be the *use* matrix where each element represents the purchases of commodity i that industry j uses as input for production. The *make* matrix $\boldsymbol{V} = [v_{ij}]$ contains information about how much commodity j is produced by each sector i. The vectors for final demand and output of commodities are $\boldsymbol{e} = [e_i]$, and $\boldsymbol{x} = [x_i]$, respectively.

The next step is to define the relations of the ecological subsystem. Let $\boldsymbol{R}$ be an array that contains the ecological commodity (i.e. CO2, solid waste, radiation, etc.) that is deposited in the environment as a residual in the production of each economic commodity; and $\boldsymbol{T}$ be the matrix for ecological commodity used by each economic sector. Note that the row sums of $\boldsymbol{T}$ represent the total amount of each commodity used in the total economy production $\bar{\boldsymbol{t}} = \boldsymbol{Ti}$.

Following the usual way to obtain the proportional (or technical) coefficients matrices, we can post-multiply each of the above by $\widehat{\boldsymbol{x}}^{-\boldsymbol{1}}$:

- The direct requirements of commodity-by-industry are defined as $\boldsymbol{B} = \boldsymbol{U}\widehat{\boldsymbol{x}}^{-1}$, where each element $[b_{ij}]$ represent the proportion of each commodity i needed to produce one-unit value in industry j.

- The industry-proportions matrix $\boldsymbol{C} = \boldsymbol{V}'\widehat{\boldsymbol{x}}^{-1}$ presents the proportional distribution of output from sector j for each commodity i.

- And, each element $[g_{ij}]$ in matrix $\boldsymbol{G} = \boldsymbol{T}\widehat{\boldsymbol{x}}^{-1}$ represents the intensity in the use of commodity k by industry j, to produce one-unit of value.

- Additionally, we can get the proportions of commodities used as inputs for production in the matrix $\boldsymbol{D} = \boldsymbol{V}'\widehat{\boldsymbol{q}}^{-1}$

In this context, the commodity-by-industry total requirement matrix is obtained with the expression $\boldsymbol{D}(\boldsymbol{I} - \boldsymbol{BD})^{-1}$. Then, $\boldsymbol{x} = \boldsymbol{D}(\boldsymbol{I} - \boldsymbol{BD})^{-1}\boldsymbol{e}$, where $\boldsymbol{e}$ is the vector for final demand of commodities. Thus, to obtain an expression of the usage of ecological commodities in the production process, as a function of the final demand of commodities, we can proceed as follows:

$$\begin{aligned}\bar{\boldsymbol{t}} &= \boldsymbol{Ti} \\ &= [\boldsymbol{G}\widehat{\boldsymbol{x}}]\boldsymbol{i} \\ &= \boldsymbol{Gx} \\ &= \boldsymbol{G}[\boldsymbol{D}(\boldsymbol{I}-\boldsymbol{BD})^{-1}\boldsymbol{e}]\end{aligned} \tag{2.58}$$

And as usual, the changes in consumption of ecologic commodities from changes in final demand of economic commodities can be represented as the differences below:

$$\Delta\bar{\boldsymbol{t}} = [\boldsymbol{GD}(\boldsymbol{I}-\boldsymbol{BD})^{-1}]\Delta\boldsymbol{e} \tag{2.59}$$

Where the matrix in brackets is the so-called *ecological input intensity* that denotes the total amount of ecological commodity k used in the production of the economic commodity i, as a result of change in one-unit value of the final demand in that economic commodity.

Concerns about the damages in ecological services from natural disasters have arisen recently. Nevertheless, this is a topic that has not yet been deeply explored by IO modellers. One of the few examples of this can be found in (A. Rose, Cao, & Oladosu, 2000), where damages from climate change are evaluated as changes in the output of forestry-related sectors. This is an unusual application of the Economic- Ecological IO model. Nevertheless, there exist a rising interest in evaluating the effects of natural hazards in ecological services, which as A. Z. Rose (2004) suggests, is a matter of environment justice, not only in the present but in an intergenerational context; which results in the sustainability of the economic systems.

2.6 MRIO and IRIO analysis with Environmental Extensions

The standard IO model can evaluate the impacts in product from changes in final demand, but within a local economy. This is, without (economic) interaction with other economies. Nevertheless, the globalised world economy establishes strong interconnections among different regions (e.g. countries), and it is increasingly evident that changes in production in one of these regions would affect other sectors' production beyond local boundaries. The main channel of transmission of those effects is the interregional (international) trade, i.e. imports and exports.

Both the Inter-Regional IO model (IRIO) and the Multi-Regional IO model (MRIO) have been used to incorporate these relationships into the IO analysis.

2.6.1 Interregional Input Output Model (IRIO)

The ARIO model aims to consider the inter-industry transactions among different regions, as well as the final demand of products from different regions. The information that is needed to process these relations are the transactions between couples of sectors (i and j) and, for the p-number of regions, the transactions between couples of regions denoted as r and s; where $r, s = 1, 2, \dots, p$. Information of the correspondent regional production ($\boldsymbol{x^r}$), and regional final demand ($\boldsymbol{f^r}$) is needed as well.

Let consider that:

- $\boldsymbol{Z}^{rs}$ is the matrix of shipped inputs from region r to region s. Each element of the matrix is $[z_{ij}^{rs}]$, denoting the input from industry i in region r, that is needed by industry j in region s. Then, this matrix represents the intra-regional transactions when $r = s$, and inter-regional transactions when $r \neq s$. Note that the double superscript is used only to distinguish origin and destiny region.

- $\boldsymbol{x}^r$ is the vector of total output in region r. Each element in $\boldsymbol{x}^r$, $[x_i^r]$, is the output of sector i produced in region r.

- $\boldsymbol{f}^r$ is the vector of final demand from region r. Each element in $\boldsymbol{f}^r$, $[f_i^r]$, represents the final demand of product from industry i in region r.

For the case of p regions we have:

- $\boldsymbol{Z} = \begin{bmatrix} \boldsymbol{Z}^{11} \dots \boldsymbol{Z}^{1s} \dots \boldsymbol{Z}^{1p} \\ \vdots \quad \vdots \quad \vdots \\ \boldsymbol{Z}^{r1} \cdots \boldsymbol{Z}^{rs} \dots \boldsymbol{Z}^{rp} \\ \vdots \quad \vdots \quad \vdots \\ \boldsymbol{Z}^{p1} \dots \boldsymbol{Z}^{ps} \dots \boldsymbol{Z}^{pp} \end{bmatrix}$, where matrices in the diagonal represent intraregional transactions, while the off-diagonal matrices represent the interregional transactions. Note that while matrices in the diagonal must be squared matrices, this condition is not necessary in the off-diagonal matrices, due to not all regions have the same industries. However, in the aggregate, the matrix $\boldsymbol{Z}$ is a squared matrix. The dimension of the matrix $\boldsymbol{Z}$ is $(\sum_r \sum_i i^r) * (\sum_r \sum_i i^r)$, where i^rindicates the industry i by region r.

- $\boldsymbol{x} = \begin{bmatrix} \boldsymbol{x}^1 \\ \vdots \\ \boldsymbol{x}^r \\ \vdots \\ \boldsymbol{x}^p \end{bmatrix}$, is the vector of total product in all regions. The dimension of the vector is $\sum_r \sum_i i^r$.

- $\boldsymbol{f} = \begin{bmatrix} \boldsymbol{f}^1 \\ \vdots \\ \boldsymbol{f}^r \\ \vdots \\ \boldsymbol{f}^p \end{bmatrix}$, is the vector of final demand for all regions with dimension $\sum_r \sum_i i^r$.

Once the information is arranged in a similar way as in the basic IO framework, we can proceed to obtain the solution of the system in an analogous way by redefining the meaning of each coefficient.

So, once again the system is $\boldsymbol{x} = \boldsymbol{Z}\boldsymbol{i} + \boldsymbol{f}$, where each row is:

$$\begin{aligned} x_i^r &= [z_{i1}^{r1} + \cdots + z_{ij}^{r1} + \cdots + z_{in}^{r1}] + \cdots + [z_{i1}^{rr} + \cdots + z_{ij}^{rr} + \cdots + z_{in}^{rr}] + \cdots \\ &\qquad + [z_{i1}^{rs} + \cdots + z_{ij}^{rs} + \cdots + z_{in}^{rs}] + [z_{i1}^{rp} + \cdots + z_{ij}^{rp} + \cdots \\ &\qquad + z_{in}^{rp}] + f_i^r \\ &= \sum_s \sum_j z_{ij}^{rs} + f_i^r \end{aligned} \tag{2.60}$$

The interregional technical coefficients are developed also in a parallel way:

Let $\boldsymbol{A}^{rs} = \boldsymbol{Z}^{rs}(\hat{\boldsymbol{x}}^s)^{-1}$, the technical coefficients for inputs shipped in region r to region s; where each element $\left[a_{ij}^{rs} = \frac{z_{ij}^{rs}}{x_j^s}\right]$ is the proportion of input from sector i in region r that industry j in region s needs to produce one-unit value of its product (x_j^s). As before, aggregating al interregional-technical coefficients matrix we get:

$$A = \begin{bmatrix} A^{\mathbf{11}} \cdots A^{\mathbf{1s}} \dots A^{\mathbf{1p}} \\ \vdots \quad \vdots \quad \vdots \\ A^{\mathbf{r1}} \cdots A^{\mathbf{rs}} \dots A^{\mathbf{rp}} \\ \vdots \quad \vdots \quad \vdots \\ A^{\mathbf{p1}} \dots A^{\mathbf{ps}} \dots A^{\mathbf{pp}} \end{bmatrix} \tag{2.61}$$

Using the expression in (2.9), the system can be expressed as:

$$\boldsymbol{x} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{f} \tag{2.62}$$

And the solution is, analogous with the standard model:

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-\mathbf{1}}\boldsymbol{f} \tag{2.63}$$

Where each element in $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ provides information about the total change in requirements of product of sector i in region r, that comes from not only the first impulse of a change in final demand of sector i product, but the additional demand of interindustrial inputs from other regions to satisfy that change in demand.

To assess the change in final demand in region r, suppose the final demand for other sectors and regions remain constant. Then, for solving the model for region r, first we can obtain an expression of other regions different from region r (where $\Delta f^s = 0$), but in terms of product from region r:

$$\begin{gathered} (\boldsymbol{I}^{ss} - \boldsymbol{A}^{ss})\boldsymbol{x}^s - \sum_{\boldsymbol{r} \neq \boldsymbol{s}} \boldsymbol{A}^{sr}\boldsymbol{x}^r = \mathbf{0} \\ \boldsymbol{x}^s = (\boldsymbol{I}^{ss} - \boldsymbol{A}^{ss})^{-\mathbf{1}} \left[\sum_{\boldsymbol{r} \neq \boldsymbol{s}} \boldsymbol{A}^{sr}\boldsymbol{x}^r \right] \end{gathered} \tag{2.64}$$

The correspondent expression for region r is:

$$(\boldsymbol{I}^{rr} - \boldsymbol{A}^{rr})\boldsymbol{x}^{r} - \sum_{s \neq r} \boldsymbol{A}^{rs}\boldsymbol{x}^{s} = \boldsymbol{f}^{r} \tag{2.65}$$

Substituting equation (2.64) in equation (2.65), we obtain an expression from changes in demand of region r, considering the trade effects among regions.

$$(\boldsymbol{I}^{rr} - \boldsymbol{A}^{rr})\boldsymbol{x}^{r} - \sum_{s \neq r} \boldsymbol{A}^{rs}\left[(\boldsymbol{I}^{ss} - \boldsymbol{A}^{ss})^{-1}\left[\sum_{r \neq s} \boldsymbol{A}^{sr}\boldsymbol{x}^{r}\right]\right] = \boldsymbol{f}^{r} \tag{2.66}$$

In the original IO model (for one region), the changes associates in production from changes in final demand were:

$$(\boldsymbol{I}^{rr} - \boldsymbol{A}^{rr})\boldsymbol{x}^{r} = \boldsymbol{f}^{r} \tag{2.67}$$

In the interregional model, from equation (2.66), we realise that there is an additional term in the demand that comes from the additional production in other regions to satisfy the original changes in final demand in region r. This is the second term in first member of the equation:

$$\sum_{s \neq r} \boldsymbol{A}^{rs}\left[(\boldsymbol{I}^{ss} - \boldsymbol{A}^{ss})^{-1}\left[\sum_{r \neq s} \boldsymbol{A}^{sr}\boldsymbol{x}^{r}\right]\right] \tag{2.68}$$

However, the high amount of data required to satisfy the IRIO model, makes virtually impossible its empirical application.

2.6.2 Multiregional Input Output Model (MRIO)

To overcome the main restriction imposed by the high data demand by the IRIO model, some statistical techniques have been implemented to obtain a model that takes into consideration the relationships among regions, but has less restrictive data requirements.

Now, the information required in the technical-regional coefficients matrix are the amount of product from industry i bought as an input in region r, to produce one-value unit of sector's j product in region r, denoted as z^r (note that only the region of destiny is referred in the superscript). This means that the information on the product's origin is not necessary in this model, and the technical coefficients can be found following a parallel way with the standard IO model: $a_{ij}^r = \frac{z_{ij}^r}{x_j^r}$. The meaning of these coefficients is the proportions of product from industry i used as input by industry j in region r to produce one-unit value of output in sector j in region r (x_j^r). A common way to obtain this information is scaling from national technical coefficients to a regional coefficients matrix, weighted by the proportion product of each destiny-subsector in the total production of destiny-sector. Assuming that a_{ij}^n is the national proportion of input from sector i needed in industry j to produce one-unit value of x_j, and assuming that sector j posses h subsectors in region r, then the weighted regional-technical coefficients can be found as follows:

$$a_{ij}^r = \frac{\sum_h a_{i(j,h)}^n \, x_{i(j,h)}^r}{x_j^r} \tag{2.69}$$

Where $x_j^r = \sum_h x_{i(j,h)}^r$. These are the elements of matrix $\boldsymbol{A}^r$, which is parallel to $\boldsymbol{A}^{rr}$ in the IRIO model when $r = s$, i.e. the elements of the diagonal in matrix $\boldsymbol{A}$ that represent intraregional transactions.

For interregional coefficients, the information is compiled in a different way due to the usual available data. The interregional table for industry $i's$ product contains the amount of input i, from region r to region s ($\boldsymbol{Z}_i = [z_i^{rs}]$), regardless of destination industry. The column sum of the s-th region contains the total amount that that region bought of good i from all other regions ($T_i^s = \sum_r z_i^{rs}$). Dividing each element of $\boldsymbol{Z}_i$ between its correspondent column sum, we get the input i that comes from region r as proportions of all input i shipped in region s: $c_i^{rs} = \frac{z_i^{rs}}{T_i^s}$.

Let $c^{rs} = \begin{bmatrix} c_1^{rs} \\ \vdots \\ c_n^{rs} \end{bmatrix}$ be a vector array that contains only one specific origin-destination for each good, where intraregional transactions arise in the case $r = s$.

With all these elements, we can construct the MRIO in an equivalent way with the IRIO model. The counterpart in MRIO model for matrix $\boldsymbol{A}^{rs}$ in IRIO model is now:

$$\hat{c}^{rs}A^{r} = \begin{bmatrix} c_1^{rs}a_{11}^{r} & \dots & c_1^{rs}a_{1n}^{r} \\ \vdots & c_i^{rs}a_{ij}^{r} & \vdots \\ c_n^{rs}a_{n1}^{r} & \dots & c_n^{rs}a_{nn}^{r} \end{bmatrix} \tag{2.70}$$

Then, the MRIO model is:

$$\begin{aligned} \boldsymbol{x} &= \boldsymbol{CAx} + \boldsymbol{Cf} \\ (\boldsymbol{I} - \boldsymbol{CA})\boldsymbol{x} &= \boldsymbol{Cf} \end{aligned} \tag{2.71}$$

Note that in this case, it is explicit the proportion of products from region r that accounts to satisfy the total final demand in other regions. Thus, the solution of the system to obtain the product as a function of the final demand is:

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{CA})^{-1}\boldsymbol{Cf} \tag{2.72}$$

Similarly, as in the IRIO model, we can have an extended expression of the model:

$$\begin{aligned} (\boldsymbol{I}^{s} - \hat{\boldsymbol{c}}^{sr}\boldsymbol{A}^{s})\,\boldsymbol{x}^{s} - \sum_{r \neq s} \hat{\boldsymbol{c}}^{sr}\boldsymbol{A}^{r}\boldsymbol{x}^{r} &= \boldsymbol{0} \\ \boldsymbol{x}^{s} = \ (\boldsymbol{I}^{s} - \hat{\boldsymbol{c}}^{sr}\boldsymbol{A}^{s})^{-1} &\left[\sum_{r \neq s} \hat{\boldsymbol{c}}^{sr}\boldsymbol{A}^{r}\boldsymbol{x}^{r}\right] \end{aligned} \tag{2.73}$$

The correspondent expression for region r is:

$$(\boldsymbol{I}^{r} - \hat{\boldsymbol{c}}^{rr}\boldsymbol{A}^{r})\,\boldsymbol{x}^{r} - \sum_{s \neq r} \hat{\boldsymbol{c}}^{rs}\boldsymbol{A}^{s}\boldsymbol{x}^{s} = \sum_{r} \hat{\boldsymbol{c}}^{sr}\boldsymbol{f}^{r} \tag{2.74}$$

Substituting equation (2.73) in equation (2.74), we obtain an expression that solves for the product in region r, from changes in demand of region r by taking into consideration the trade effects among regions.

$$(I^r - \hat{c}^{rr}A^r)x^r - \sum_{s\neq r}\hat{c}^{rs}A^s\left[(I^s - \hat{c}^{sr}A^s)^{-1}\left[\sum_{r\neq s}\hat{c}^{sr}A^r x^r\right]\right] = \sum_{r}\hat{c}^{sr}f^r \tag{2.75}$$

Because we had stated the similarity between $\boldsymbol{A^{rr}}$ and $(\boldsymbol{\hat{c}^{rr}A^r})$, as expressed in IRIO model, the term $(\boldsymbol{I}^r - \boldsymbol{\hat{c}^{rr}A^r})$ in equation (2.75), associated with levels of $\boldsymbol{x^r}$, represents the impact associated to changes in final demand on the regional economy, but without considering the multiregional effects associated with trade. The additional term, $\sum_{s\neq r}\boldsymbol{\hat{c}^{rs}A^s}\left[(\boldsymbol{I}^s - \boldsymbol{\hat{c}^{sr}A^s})^{-1}\left[\sum_{r\neq s}\boldsymbol{\hat{c}^{sr}A^r x^r}\right]\right]$, refers to this interregional feedback, originated from changes in demand in other regions as suppliers of regions, where the first impulse of final demand was originated. It is important to note that unlike the IRIO model, the impacts in region r's output in the above expression accounts for final demand changes in all regions, weighted by the share of that demands that are fulfilled from region r. This is, instead of seeing the left term in equation (2.75) as the impact from changes in final demand of a certain region (as usually happens in IO framework), it is the impact on output level of a certain region from changes in the demand of its products in all other regions.

2.6.2.1 Environmental extensions

As we can see, the MRIO model takes into consideration (under some assumptions) the imports and exports for intermediate and final demand among regions. Regarding environmental impacts, the emissions embedded in production in one region can be attributed to production or consumption in other regions. Thus, based on Ahmad and Wyckoff (2003), we can introduce the concepts of the Environmental IO model previously developed, to assess the environmental impacts among regions from changes in their final demands.

In the Environmental IO model, we have defined the matrix $\boldsymbol{D}^p = [d^p_{kj}]$, where each element $[d^p_{kj}] = [p_{kj}/x_j]$ represents the physical units of pollutant k embedded in the production of each unit value of industry j's product. Supposing that we have got this information for each of the p regions ($\boldsymbol{D}^{\boldsymbol{r}\boldsymbol{p}*} = \boldsymbol{D}^{\boldsymbol{r}}\boldsymbol{L}$, where r denotes the information for that region), the emissions of pollutant k generated in region r, associated to changes in final demand in other regions [1, …, p] can be inferred from the general solution to the MRIO model.

From the expression $\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{C}\boldsymbol{A})^{-\mathbf{1}}\boldsymbol{C}\boldsymbol{f}$, the total impact in production from changes in final demand is given by the expression $(\boldsymbol{I} - \boldsymbol{C}\boldsymbol{A})^{-\mathbf{1}}\boldsymbol{C}$. This is the parallel expression to matrix $\boldsymbol{L}$ in the Environmental IO model. Then, using regional information for pollution associated to production in each region ($\boldsymbol{D}^{\boldsymbol{r}\boldsymbol{p}*}$), the total impact in pollution ($\boldsymbol{D}^{*}$) associated to changes in final demand in the multiregional model is:

$$\boldsymbol{D}^{*} = \boldsymbol{D}(\boldsymbol{I} - \boldsymbol{C}\boldsymbol{A})^{-\mathbf{1}}\boldsymbol{C}, \qquad (2.76)$$

Where
$$\boldsymbol{D} = \begin{bmatrix} \boldsymbol{D}^{\mathbf{1}} \cdots \mathbf{0} \ldots \mathbf{0} \\ \vdots \quad \vdots \quad \vdots \\ \mathbf{0} \cdots \boldsymbol{D}^{\boldsymbol{r}} \ldots \mathbf{0} \\ \vdots \quad \vdots \quad \vdots \\ \mathbf{0} \ldots \mathbf{0} \ldots \boldsymbol{D}^{\boldsymbol{p}} \end{bmatrix}$$

Therefore, the multi-regional effects from changes in demand of products in region r are apportioned in the following expression:

$$\boldsymbol{D}^{\boldsymbol{r}}(\boldsymbol{I}^{r} - \hat{\boldsymbol{c}}^{\boldsymbol{rr}}\boldsymbol{A}^{\boldsymbol{r}}) - \sum_{\boldsymbol{s}\neq\boldsymbol{r}}\left[\sum_{\boldsymbol{r}\neq\boldsymbol{s}}\boldsymbol{D}^{\boldsymbol{r}}\hat{\boldsymbol{c}}^{\boldsymbol{sr}}\boldsymbol{A}^{\boldsymbol{r}}\right]\ (\boldsymbol{I}^{s} - \hat{\boldsymbol{c}}^{\boldsymbol{sr}}\boldsymbol{A}^{\boldsymbol{s}})^{-\mathbf{1}}\hat{\boldsymbol{c}}^{\boldsymbol{rs}}\boldsymbol{A}^{\boldsymbol{s}} = \sum_{\boldsymbol{s}}\hat{\boldsymbol{c}}^{\boldsymbol{rs}}\boldsymbol{f}^{\boldsymbol{s}} \qquad (2.77)$$

Where:

- $\boldsymbol{D}^{\boldsymbol{r}}(\boldsymbol{I}^{r} - \hat{\boldsymbol{c}}^{\boldsymbol{rr}}\boldsymbol{A}^{\boldsymbol{r}})$**,** represents environmental changes in the regions which products suffered a change in demand. This is the equivalent change in the model for only one region.

- $\sum_{\boldsymbol{s}\neq\boldsymbol{r}}[\sum_{\boldsymbol{r}\neq\boldsymbol{s}}\boldsymbol{D}^{\boldsymbol{r}}\hat{\boldsymbol{c}}^{\boldsymbol{sr}}\boldsymbol{A}^{\boldsymbol{r}}]\ (\boldsymbol{I}^{s} - \hat{\boldsymbol{c}}^{\boldsymbol{sr}}\boldsymbol{A}^{\boldsymbol{s}})^{-\mathbf{1}}\hat{\boldsymbol{c}}^{\boldsymbol{rs}}\boldsymbol{A}^{\boldsymbol{s}}$, is the embedded pollution in interregional trade. This is an additional impact due demand for inputs from other regions to satisfy the change in production in region r. This means that leaving aside the interregional trade, the estimation of environmental impact is being underestimated.

2.6.2.2 Applications in natural disasters

With strong interregional economic relations, changes in output level of one region can affect those of others. As a result, the multiregional analysis has become a necessity in disaster impact analysis. The most common regional model used is the Multi-Regional IO Model (MRIO) which contains data about inputs bought by sector i in region r from sector j (it does not matter where they come from); and even when this data is not available, the technical coefficients can be calculated using the product mix approach (Miller & Blair, 2009). This has made the assessment of higher order losses possible in the context of a natural disaster affecting small regions rather than national economies, and the dispersed effects in multiple regions (Y. Y. Haimes et al., 2005; Okuyama, 2004). For example, (Crowther & Haimes, 2010) go beyond the Inoperability I-O Model (IIM) to make the multiregional dimension explicit in their Multiregional Inoperability Input-output Model (MIIM). They deal specifically with the lack of spatial explicitness in previous models. This makes the model more accurate at a regional level (or even down to the county level), where in the past the impact and damage were considered as homogenous or uniform across the regions. The conclusion is that it benefits providences for better preparedness at a multiregional level. The MIIM allows consideration of the relationships between different regions. In its initial version, it was a demand-driven model, however, the authors argue that inoperability is more an issue of lost supply value, which result in an extension of the MIIM, to take into consideration the inoperability in production from bottlenecks in the production (supply-chain). One of the limitations of the model is that the dynamic aspect of recovery is not modelled.

Furthermore, the information in the regional extensions of the IO model can be enriched with Geographical Information Systems (GIS), as suggested by (Steenge & Bočkarjova, 2007). This would improve the accuracy of the Event Account Matrix (EAM), an element containing the proportion of productivity losses in each sector after a disaster. In (Veen & Logtmeijer, 2003), the GIS enriches the risk analysis in a Province of South-Holland, where the information is extrapolated with socioeconomic data to define hotspots, which are interpreted as a visualization of vulnerability to flooding.

2.7 IO approach for impact assessment of climate extreme events. Indirect cost appraisal

As it was stated at the beginning of this section, the first version of the IO model is a static and demand-driven model. Nevertheless, the damage caused by a natural disaster imposes imbalances in the economy that usually affects the supply side of the productive chain, leading to bottlenecks in production and disruption to the equilibrium in the economy during recovery. In this section, it will be presented the further research on the specific situations that arise after a disaster, and the way they have been incorporated under the framework of IO analysis.

2.7.1 Modelling risk

The occurrence and intensity of natural disasters is often difficult to predict with any level of certainty. Taking advantage of the structure of the IO model and the available data, some extensions have been made to explicitly incorporate the inherent risk from natural disasters. Several authors (Y. Haimes & Jiang, 2001; Y. Y. Haimes et al., 2005; R. J. Santos, 2006) have developed a measure of the expected inoperability, based on the risk that the system becomes unable to perform its planned ‘natural or engineered functions’. Based on this concept, the IIM assumes a direct relationship between the number of transactions and the interdependency between economic sectors.

The matrix of technical coefficients ($\boldsymbol{A}$) becomes into a matrix where the coefficients represent the strengths of the relationships between sectors, ($\boldsymbol{A}^*$), in which every element [a_{ij}^*] represents the inoperability in sector i attributable to sector j. In its initial version, this is a demand-driven and static model where the equilibrium is assumed at each time step along the recovery time (J. R. Santos & Haimes, 2004). Even with its rigidities, the IIM has proved useful in the assessment of inoperability among economic sectors, to prepare for or mitigate against the adverse impacts of negative shocks when identifying the most vulnerable sectors (Crowther et al., 2007).

2.7.2 Time-dynamic extensions

As mentioned before, the consequences of a natural disaster leave its footprint in the economy for a certain period of time, depending on the characteristics of the disaster (mainly duration and intensity). For example, an earthquake may last only a few seconds while its consequences can be realised for a long time afterwards. On the other hand, the consequences of a flood that last for some weeks can be less harmful if the infrastructure is not seriously damaged (Okuyama, 2009). One of the principal challenges is to understand the process by which the economy recovers, since this largely determines the indirect costs and, therefore the total costs. Even when the standard IO model is static, Leontief himself developed a dynamic extension of it (Miller & Blair, 2009; A. Z. Rose, 1995). Other later extensions to deal with these constraints are the Sequential Inter-industry Model (SIM) (Okuyama, 2004; Romanoff & Levine, 1981); a continuous-time formulation of a regional econometric input–output model (REIM); and the Dynamic Inoperability IO model (DIIM) (Y. Y. Haimes et al., 2005; Okuyama, 2007; J. R. Santos & Rehman, 2012; R. J. Santos, 2006; Xu et al., 2011). Other important developments in this field were made by (Stéphane Hallegatte, 2008), who uses a time-scaled approach to model the recovery path, in which supply constraints and bottlenecks are both considered.

2.7.3 Modelling Imbalances

The basic IO model and some of the mentioned extensions represent a situation where the economy is in equilibrium and all production is consumed by intermediate and final demand, even in the disaster aftermath. However, the damage caused by natural disasters usually leads a structural disruption in the normal functioning of the economy. The production capacity is reduced and imbalances between supply and demand arise. In practice, it has been noted that these imbalances sometimes remain in until complete recovery of the economy (Li et al., 2013; Okuyama, 2009). To deal with the consequences of damaged production capacity, bottlenecks, and imbalances in general, important adjustments to the IO model have been made. With this purpose, the notion of the Basic Equation was developed as a modification of the IO closed model (Bockarjova, Steenge, & van der Veen, 2004; Steenge & Bočkarjova, 2007), as an start point of the economy before the disaster, and as a path towards equilibrium. A further development from the Basic Equation was the modelling of the impact of a natural disaster with an Event Account Matrix (EAM). This is an IO compatible element to assess the impact of a natural disaster (or a shortage in productive capacity in general) on the economic system (Cole, 2003; Stéphane Hallegatte, 2008; Li et al., 2013; Steenge & Bočkarjova, 2007). The aim is to generate a matrix with the proportion of the damage that each sector suffered, which allows an estimation of the imbalances between the productive capacity and the consumption in an economy after a shock; to subsequently develop and simulate a recovery strategy. Allowing for the substitution of imports in some goods and services, the modelling extensions deal with constrains in production and bottlenecks that arises after the disaster. The effectiveness of the strategy and recovery path largely depends on the reallocation criteria of the remaining productive factors (Batey & Rose, 1990; Gosh, 1958; Stéphane Hallegatte, 2008; Stephane Hallegatte & Przyluski, 2010; Li et al., 2013).

Other treatments of changes in supply are developing as extensions of the IIM. As instance, Leung et al. (2007) use a price-changing approach to try to overcome the main limitations of the demand-driven IO model. When the model is treated as a demand-driven, changes in quantities are modelled; while changes in prices are evaluated when it is treated as supply-driven model. This is because changes in quantity from changes in value added (changes in supply side) have never been totally accepted, so that the model is thought as a price-change model. However, cascade effects can be measured from changes in prices from the supply side to changes in quantities in final demand, and vice versa. The concept of price-elasticity is used for this purpose.

For example, Xu et al. (2011) developed an extension of the classical Inoperability IO model. The extension is a supply–driven model, which makes it more suitable for a situation where there are imbalances (disequilibrium between production capacity and demanded), and they develop it in the frame of previous dynamic models. Their model, the Dynamic Inoperability Input-Output Model (DIIM), accounts for the recovery path through the time. The first modification is based on the Inoperability Input-Output Model (IIM), which is not dynamic but is driven by changes in value-added instead of changes in final demand. Even if this price model only captures the changes in the prices of the value added (labour, taxes, etc.), it can be suitable to analyse the recovery path (of economic sectors) after a disaster. What it is not explicit in the model is if it is comparable with the demand-driven model, because the impact in the economy caused by a disaster is modelled as an increase in the level of prices of economic sectors. One of the weaknesses of this model is the fact that the recovery time for each affected sector is assumed. This is usually one of the expected results from the analysis, instead of an input. However, J. R. Santos and Rehman (2012) extended the model and made their analysis based on survey data to calibrate or estimate the time for recovery in the affected sectors.

Recently, Li et al. (2013) developed a Dynamic Inequalities approach , an IO base model which presents *'a theoretical route map for imbalanced economic recovery'*. The main achievement of their model is the consideration of supply constraints (using the EAM concept) and changes in final demand. They also consider the imbalances in the economy along the recovery time. In this sense, it is a time-dynamic model. Substitution in imports is also allowed for the *recovery* demand. Its strengths lie in its ability to incorporate many of the situations arising in the economy after a disaster, this constitutes the theoretical and analytical framework that will be the base for the analysis along the course of this thesis, to further extend it to reach the ultimate aim set out in this research.

2.7.4 Recent work on impact assessment by using IO modelling

During the time of the development of this thesis, some other extensions for impact assessment have been developed. The three most relevant examples are explored below.

Erik Dietzenbacher and Lahr (2013) apply the method of hypothetical extractions to the analysis of impact assessment. The method proposes to *extract*, partially or totally, the intermediate transactions of a sector within the economy. It achieves this by replacing the row or column of the affected sector with zeros (or smaller proportions of the original value). A new level of production is calculated under these conditions. The change from the original level of production constitutes the effect of the disaster in the economy. The main contribution of this approach is that it consistently considers the forwards effects of a shock within the demand-driven IO model. However, Oosterhaven and Bouwmeester (2016) have argued that the assessment of forward effects with this method is flawed, as it measures the backwards effects of the reduction of intermediate sales of an industry instead of the forward effects of the reduction of inputs from the affected industry to the other purchasing industries.

E.E. Koks, Bockarjova, de Moel, and Aerts (2014) propose to use a Cobb-Douglas function to estimate the direct damages from labour and capital constraints, and the indirect damages incurred during the recovery process are derived through the ARIO model (Stéphane Hallegatte, 2008). This approach provides consistency within the economics' theory to the appraisal of effects in a flow variable (the production flow) that arise from damages in a stock variable (capital stock). It also constitutes a good comparable approach to the flood footprint model, as it also incorporates restrictions in the productive capacity of labour and similar recovery process assessed with the ARIO model. It should be noted that the consideration of the relationship between the productive factors and the production level through the Cobb-Douglas function, is to convert the physical damages to the capital stock into damages to the production flow. This approach would also be useful in modelling of the recovery process, by converting the capital investment in recovery into restoration of the production capacity. This could provide with a comparable approach related to the introduction of the capital matrix in this thesis.

More recently, Oosterhaven and Bouwmeester (2016) propose a new approach, which is based on non-linear programming that minimises the information gain between the pre- and post-disaster situations of economic transactions. The model is successful in reproducing the recovery towards the pre-disaster economic equilibrium. To date, the model has only been tested hypothetically. Further development is required for applications to real cases, as some aspects of disaster impact analysis are excluded, such as the damages to residential capital, or the recovery of productive capacity of labour.

Chapter 3 Methodology. Flood Footprint Assessment Framework

The purpose of this chapter is to fulfil Objective 1, which is the development of flood footprint model.

In this section, the rationale of the standard Flood Footprint model, as well as the development stages to reach the final Multi Regional Flood Footprint model, is presented.

The standard version captures the direct and indirect damages in the flooded region, without consideration of interaction with other regions. This version was applied for the analysis of the first case study, the flood footprint appraisal of the 2007 floods in Yorkshire and The Humber region, and has been already published in:

Mendoza-Tinoco, D., Guan, D., Zeng, Z., Xia, Y., Serrano, A. (2017) Flood footprint of the 2007 floods in the UK: The case of the Yorkshire and The Humber region, in Journal of Cleaner Production 168 pp. 655-667 https://doi.org/10.1016/j.jclepro.2017.09.016

The second phase of the methodology development comprises the simultaneous analysis of several regions, although there is still no interaction between the regions. This is very useful in the case a disaster affects several regions with autonomous economic administrations. Additionally, the concept of capital matrix is introduced here to provide methodological consistency to transit from a flow variable (production) towards a stock variable (the capital stock). This version is applied for the case studies of the Central Europe floods in 2009, and the Xhynthia windstorm affecting Europe in 2010.

The final stage incorporates the Multi Regional analysis, which implicate the interaction of the affected region with other regions/countries. This version is applied to a projection of different climate change scenarios for the city of Rotterdam, in the Netherlands.

It must be noted that the different model versions are not a linear succession of each stage. The analysis of multiple regions provides a better understanding of the regional dimension of a disaster, but it still lacks analysis for regional economic interconnections. On the other hand, the Multi Regional Flood Footprint accounts for national damages arising from a regional disaster, and then the repercussions to other national economies. This is due to the lack of regional IO tables with intra and international trade data prevents in most cases the Multi Regional analysis of multiple affected regions.

3.1 Standard Flood Footprint model

The flood footprint is based on the IO model. Let us start with the assumptions considered in the flood footprint modelling.

As the model relies on the IO model, some assumptions are inherited:

- The Leontief type production functions (or prefect complements production functions) assumes a fixed proportion of productive factors for all levels of production.
- We assume that the technology is fixed along the recovery time. This is a common undertaken assumption in IO modelling for periods below 5 years.
- The model considers changes in quantities, not prices, although the amounts are presented in monetary values. This is, the model assumes fixed prices.
- The model considers that each industry produces one homogenous product. This is, the technology coefficient of each industry represents the average technology among the different goods produced in the industry.
- Regarding labour, it is assumed the labour and wages are homogenous within each industry. Additionally, it is assumed each employee works 8 hours 5 days per week, and the productivity of labour is fixed.

The IO model is founded on the basic idea of the circular flow of the economy in equilibrium. The IO tables present the inter-industrial transactions of the whole economy in a linear array. In mathematical notation, it is presented as:

$$\boldsymbol{x} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{f} \tag{3.1}$$

Where $\boldsymbol{x}$ is a vector representing the total production of each industrial sector[16], $\boldsymbol{A}\boldsymbol{x}$ represents the intermediate demand vector, where each element of the matrix $\boldsymbol{A}$, $[a_{ij}]$, refers to the

[16] In the modelling, it is assumed that each sector produces only one uniform product.

technology showing product i needed to produce one unit of product j. Finally, $\boldsymbol{f}$ indicates final demand vector.

Based on the IO modelling, the assessment of the damage in *flood footprint* modelling departs from the *Basic Equation*, a concept developed by Steenge and Bočkarjova (2007). This is a closed[17] IO model that represents an economy in equilibrium. The equilibrium implies that total production equals total demand with the full employment of productive factors, including both capital and labour, as in equation (3.2).

$$\begin{bmatrix} \boldsymbol{A} & \boldsymbol{f}/l \\ \boldsymbol{l}' & 0 \end{bmatrix} \begin{pmatrix} \boldsymbol{x} \\ l \end{pmatrix} = \begin{pmatrix} \boldsymbol{x} \\ l \end{pmatrix} \tag{3.2}$$

and

$$l = \boldsymbol{l}'\boldsymbol{x} \tag{3.3}$$

Where $\boldsymbol{l}'$ is a row vector of *technical labour* coefficients for each industry, showing the relation of labour needed in each industry to produce one unit of product: $\left[\frac{L_i}{x_i}\right]$. L_i is the industrial level of employment. The scalar l is the total level of employment in the economy.

All inter-industrial flows of products as well as industrial employment are considered as the necessary inputs involved in the production of each unit of output. A linear relation between the productive factors (labour and capital) and the output in each sector is assumed in IO analysis, suggesting that inputs should be invested in fixed proportions for proportional expansion in output.

However, this equilibrium is broken after a disaster, and inequalities arise between productive capacity and demand. In the next section, we introduce the possible sources of these inequalities.

3.1.1.1 Sources of post-disaster inequalities

After a disaster, market forces become imbalanced, leading to gaps between supply and demand in different markets. The causes for these imbalances may be varied, and they constitute the origin of the ripple effects that permeate the economy of the flooded region.

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[17] Here, *closed* means that the primary productive factors (labour) are explicitly considered within the model.

3.1.1.2 Labour Productivity Constraints

The production function in the IO model assumes a complements-type technology where the productive factors – labour and capital – maintain a fixed relationship in the production process. Constraints in any of the productive factors will produce, therefore, a proportional decline in productive capacity, even when other factors remain fully available. Therefore, labour constraints after a disaster may impose severe knock-on effects on the rest of the economy. This makes labour constraints a key factor to be considered in disaster impact analysis. In the *flood footprint* model, these constraints can arise from employees' inability to work as a result of illness or death, or from commuting delays due to damaged or malfunctioning transport infrastructure. In the model, the proportion of surviving production capacity from the constrained labour productive capacity ($\boldsymbol{x}_{\boldsymbol{l}}^{\boldsymbol{t}}$) after the shock is:

$$\boldsymbol{x}_l^t = (\boldsymbol{i} - \boldsymbol{\Gamma}_{\boldsymbol{l}}^{\boldsymbol{t}}).* \boldsymbol{x}^{\boldsymbol{0}} \tag{3.4}$$

and

$$\boldsymbol{\Gamma}_l^t = (\boldsymbol{l}^{\boldsymbol{0}} - \boldsymbol{l}^{\boldsymbol{t}})./\boldsymbol{l}^{\boldsymbol{0}} \tag{3.5}$$

Where $\boldsymbol{\Gamma}_{\boldsymbol{l}}^{\boldsymbol{t}}$ is a vector where each element contains the proportion of labour that is unavailable at each time t after the flooding event. The vector $\boldsymbol{i}$ is a vector of ones of the same dimension as $\Gamma_l^{\boldsymbol{t}}$, so that the vector $(\boldsymbol{i} - \boldsymbol{\Gamma}_{\boldsymbol{l}}^{\boldsymbol{t}})$ contains the surviving proportion of employment at time t. $\boldsymbol{x}^{\boldsymbol{0}}$ is the pre-disaster level of production.

The proportion of the surviving productive capacity of labour is thus a function of the loss from the sectoral labour force and its pre-disaster employment level. Following the fixed proportion assumption of the production functions, the productive capacity of labour after the disaster ($\mathbf{x}_l^t$) will be a linear proportion of the surviving labour capacity at each time step.

3.1.1.3 Capital Productivity Constraints

Similar to labour constraints, productive capacity from industrial capital during the flooding aftermath ($\boldsymbol{x}_{cap}^t$) will be constrained by the surviving capacity of the industrial capital. The share of damage to each sector are disclosed in the event account vector (EAV), following Steenge and Bočkarjova (2007). Then, the remaining production capacity of industrial capital at each time-step, is:

$$\boldsymbol{x}_{\boldsymbol{cap}}^{\boldsymbol{t}} = \left(\boldsymbol{I} - \boldsymbol{\Gamma}_{\boldsymbol{cap}}^{\boldsymbol{t}}\right) * \boldsymbol{x}^{\boldsymbol{0}} \tag{3.6}$$

where
$$\boldsymbol{\Gamma}_{cap}^{t} = (\boldsymbol{k}^{\boldsymbol{0}} - \boldsymbol{k}^{\boldsymbol{t}})./\boldsymbol{k}^{\boldsymbol{0}} \tag{3.7}$$

Where, $\boldsymbol{x}^{\boldsymbol{0}}$ is the pre-disaster level of production, $\boldsymbol{\Gamma}_{\boldsymbol{cap}}^{\boldsymbol{t}}$ is the EAV, a column vector showing the share of damages of productive capital in each industry. $\boldsymbol{k}_{\boldsymbol{0}}$ is the vector of capital stock in each industry in the pre-disaster situation, $\boldsymbol{k}^{\boldsymbol{t}}$ is the surviving capital stock in each industry at time t during the recovery process.

During the recovery, the productive capacity of industrial capital is restored gradually through both local production/reconstruction and imports.

3.1.1.4 Post-disaster Final Demand

On the other side of the economic system, final demand may vary for certain reasons. On the one hand, the recovery process involves the reconstruction and replacement of damaged physical capital, which increases the final demand for those sectors involved in the reconstruction process, namely, the *reconstruction demand,* $\mathbf{f}_{\mathbf{rec}}$. On the other hand, final demand may also decrease after a disaster's occurrence. Based on Li et al. (2013), it has been noted that after a disaster's occurrence, strategic adaptive behaviour would lead people to ensure their continued consumption for essential commodities, such as food and medical services, while reducing consumption for other non-essential products.

In the model, we consider the adaptive consumption behaviour of households. Here, the demand for non-basic goods is assumed to decline immediately after the disaster, while consumption in industries providing food, energy, clothing and medical services remain at pre-disaster levels.

Recovery in household consumption is driven by two complementary processes. For consumption adaptation, we consider a short-run tendency parameter ($\mathbf{d}_1^t$), which is modelled at the rate of recovery in consumption at each time step. The rationale here is that consumers restore their consumption according to market signals about the recovery process. Likewise, a long-run tendency parameter ($\mathbf{d}_2^t$) is calculated as a *recovery gap,* i.e., the total demand minus the total production capacity compared against the total demand at each time step. Therefore, the expression for dynamic household consumption recovery is:

$$\boldsymbol{f}_{hh}^t = (\mu^0 + \boldsymbol{d}_1^t + \boldsymbol{d}_2^t) .* \boldsymbol{c}^0 \qquad (3.8)$$

Where the parameter μ^0 expresses the reduced proportion of household demand (a parameter similar to the EAM) over time, and the vector $\mathbf{c}^0$ represents the pre-disaster level of household expenditure on products by industrial sector.

The rest of the final demand categories recover proportionally to the economy, based on the contribution of each category to pre-disaster final demand. It is essential to note the trade-off between the resources allocated to final demand and to reconstruction purposes. The adapted total final demand ($\mathbf{f}^{\mathrm{t}}$), then, is modelled as follows:

$$\boldsymbol{f^t} = \sum_k \boldsymbol{f_k^t} + \boldsymbol{f_{rec}^t} \qquad (3.9)$$

where $\mathbf{f}^{\mathrm{t}}$ is the adapted total final demand at each time step t, including the reconstruction demand for industrial and residential damaged capital ($\mathbf{f_{rec}^t} = \mathbf{f_{cap}^t} + \mathbf{f_{hh}^t}$). It also includes the final demand for all final consumption categories, indicated by the summation $\sum_k \boldsymbol{f}_k^t$, where the subscript k refers to the vector of each category of final consumption. $k = 1$ is for the adapted household consumption ($\boldsymbol{f}_{hh}^t$), $k = 2$ is for government expenditure, $k = 3$ is for investment in capital formation, and $k = 4$ is for external consumption or exports.

The adapted total demand for each sector, ($\boldsymbol{x}_{td}^t$), can thus be interpreted as follows:

$$x_{td}^t(i) = \sum_{j=1}^{n} a_{ij} x_{td}^t(j) + f^t(i) \qquad (3.10)$$

Equations (3.4) to (3.10) describe the changes on both sides of the economy's flow – production and consumption – where imbalances in the economy after a disaster arise from the differences in the productive capacity of labour, the productive capacity of industrial capital, and changes in final demand. From this point, the restoration process starts to return the economy to its pre-disaster equilibrium and production level.

3.1.2 Post-disaster recovery process

The following section describes the process of recovery. Here, an economy can be considered as recovered once its labour and industrial production capacities are in equilibrium with total demand and its production is restored to the pre-disaster level. How to use the remaining resources to achieve pre-disaster conditions is modelled based on a selected rationing scheme.

Let us start this section with the assumptions related with the recovery modelling. They include the following:

- Given the Leontief type production functions, it is assumed that the proportion of capital damaged in an industry equals the proportion in which the production of that sector is constrained. This is basically how the EAV is constructed.
- After the disaster, we assume the replaced capital is the same that was destroyed, which means, the technology remains the same after the disaster.
- It is assumed that the economy recovers once it reaches the pre-disaster level of production and equilibrium.
- The model assumes that imports contributes in the recovery efforts in the same proportion as imports contributes to the economy in the prior the disaster.
- The allocation of remaining production is distributed in a priority-proportional distribution, which means the interindustry trade is attended prior final demand, and categories of final demand are attended in the same proportion as prior the disaster. This is widely discussed in the section 3.1.2.1, regarding the Rationing Scheme.

The following section describes the process of recovery. Here, an economy can be considered as recovered once its labour and industrial production capacities are in equilibrium with total demand and its production is restored to the pre-disaster level. How to use the remaining resources to achieve pre-disaster conditions is modelled based on a selected rationing scheme.

The first step is to determine the available production capacity in each period after the disaster. Within the context of Leontief production functions, the productive capacity is determined by the minimum capacity of both productive factors, capital and labour, as shown below:

$$\boldsymbol{x}_{tp}^{t} = min\{\boldsymbol{x}_{cap}^{t}, \boldsymbol{x}_{l}^{t}\} \tag{3.11}$$

Secondly, the level of the constrained production capacity is compared with the total demand to determine the allocation strategy for the remaining resources and for reconstruction planning. The rules during this process constitute what it is called the *rationing scheme*, that will be described below.

3.1.2.1 Rationing scheme

The recovery process requires allocating the remaining resources to satisfy society's needs during the disaster's aftermath. Thus, the question of how to distribute and prioritize the available production based on the remaining capacity and final demand becomes essential, as recovery time and indirect costs can vary widely under different rationing schemes.

This thesis used a *proportional-prioritization* rationing scheme that first allocates the remaining production among the inter-industrial demand ($\mathbf{Ax}_{\mathrm{tp}}^{\mathrm{t}}$) and then attends to the categories of final demand[18]. This assumption is built on the rationale that business-to-business transactions are prioritised, based on the observation that these relations are stronger than business-to-client relationships (Stéphane Hallegatte, 2008; Li et al., 2013).

Thus, when calculating the productive possibilities of the next period, the actual production is first compared with inter-industrial demand. If $\mathrm{O^t(i)} = \sum_{\mathrm{j}} \mathrm{A(i,j)x_{tp}^t(j)}$ is the production required in industry i to satisfy the intermediate demand of the other industries, two possible scenarios may arise after the disaster (Hallegatte, 2008):

The first scenario occurs when $x_{tp}^{t}(i) < O^{t}(i)$, in which case the production from industry i at time t in the post-disaster situation ($x_{tp}^{t}(i)$) cannot satisfy the intermediate demands of other industries. This situation constitutes a bottleneck in the production chain, where production in

[18] We assume here that the productivity of any of the productive factors does not change during the recovery process, as is the case with Leontief production functions. We also assume that the disaster happens just after time t=0 and that the recovery process starts at time t=1.

industry j is then constrained by $\frac{x_{tp}^{t}(i)}{O^{t}(i)} x_{tp}^{t}(j)$, where $\frac{x_{tp}^{t}(i)}{O^{t}(i)}$ is the proportion restricting the production in industry j, $x_{tp}^{t}(j)$. This process proceeds for each industry, after which there must be consideration of the fact that industries producing less will also demand less, in turn affecting and reducing the production of other industries. The iteration of this process continues until production capacity can satisfy this *adapted* intermediate demand and some remaining production is liberated to satisfy part of the final and *reconstruction* demand and increase the productive capacity in the next period. This situation leads to a partial equilibrium, where level of the adapted intermediate demand is defined as $\boldsymbol{A}\boldsymbol{x}_{tp}^{t^*}$, where the asterisk in $\boldsymbol{x}_{tp}^{t^*}$ represents the adapted production capacity that provides the partial equilibrium, and is smaller than the actual production capacity ($\boldsymbol{x}_{tp}^{t}$) from equation (3.11). This process continues until the total production available at each time, $x_{tp}^{t}(i)$, can satisfy the intermediate demand at time t, O^{t}.

The second scenario occurs when $x_{tp}^{t}(i) > O^{t}(i)$. Then, the intermediate demand can be satisfied without affecting the production of other industries.

In both cases, the remaining production after satisfying the intermediate demand is proportionally allocated to the recovery demand and to other final demand categories in accordance with the following expressions:

$$\left(\boldsymbol{x}_{tp}^{t} - \boldsymbol{A} * \boldsymbol{x}_{tp}^{t}\right) .* \ \boldsymbol{f}_{k}^{0} ./ \left(\sum_{k} \boldsymbol{f}_{k}^{0} + \boldsymbol{f}_{rec}^{t}\right) \tag{3.12}$$

$$\left(\boldsymbol{x}_{tp}^{t} - \boldsymbol{A} * \boldsymbol{x}_{tp}^{t}\right) .* \ \boldsymbol{f}_{rec}^{t} ./ \left(\sum_{k} \boldsymbol{f}_{k}^{0} + \boldsymbol{f}_{rec}^{t}\right) \tag{3.13}$$

Equation (3.12) refers to the distribution of product to the k categories of final demand, while equation (3.13) refers to the proportion of available product that is designated to reconstruction.

The expression $\left(\mathbf{x}_{\mathrm{tp}}^{\mathrm{t}} - \mathbf{A} * \mathbf{x}_{\mathrm{tp}}^{\mathrm{t}}\right)$ refers to the production left after satisfying the intermediate demand, and $\sum_{k} \boldsymbol{f}_{k}^{0}$ refers to the total final demand in the pre-disaster period, so that the production left after satisfying intermediate demand is allocated among the categories of final demand following the proportions of pre-disaster condition, plus the consideration of the reconstruction needs for recovery ($\boldsymbol{f}_{rec}^{t}$). Note that for the first scenario, the expression $\mathbf{A} * \mathbf{x}_{\mathrm{tp}}^{\mathrm{t}}$ represents the *adapted intermediate demand (*$\boldsymbol{x}_{tp}^{t^*}$*)*, which is smaller than the actual production capacity, $\mathbf{x}_{\mathrm{tp}}^{\mathrm{t}}$.

Part of the unsatisfied final demand is covered by imports, some of which contribute to the recovery when allocated to *reconstruction demand*.

3.1.2.2 Imports

In the *flood footprint* model, imports support the reconstruction process by supplying some of the inputs that are not internally available to meet *reconstruction* demand. Additionally, if the damaged production capacity is not able to satisfy the demand of final consumers, they will rely on imports until internal production is restored and they can return to their previous suppliers.

There are some assumptions underlying imports. First, imports will be allocated proportionally among final demand categories and reconstruction demand. Second, commodities from other regions are assumed to be always available for provision at the maximum rate of imports under the pre-disaster condition. Third, there are some types of goods and services that, by nature, are usually supplied locally (such as utilities and transport services), making it infeasible to make large scale adjustments over the time scale of disaster recovery. Finally, imports are assumed to be constrained by the total *importability capacity,* which here is defined as the survival productive capacity of the transport sectors (see equation (3.14)). The assumption is that the capacity of transporting goods is proportional to the productive capacity of the sectors related with transport, so that if the production value of sectors related with transport services is contracted by x% in time t, the imports will contract by the same proportion, in reference to the pre-disaster level of imports, $\boldsymbol{m}^t$.

$$\boldsymbol{m}^t = \left(\frac{x_{tran}^{*(t)}}{x_{tran}^{0}} * \boldsymbol{m}^0 \right) \tag{3.14}$$

Where $\mathbf{m}^0$ is the vector of pre-disaster imports, and $\mathrm{x}_{\mathrm{tran}}^{0}$ and $\mathrm{x}_{\mathrm{tran}}^{*(t)}$ are the scalars, denoting the pre and post-disaster production capacities of the sectors related with transport. The subscript $tran$ refers to aggregated transport sectors by land, water and air. If sectors related with transport are two or more, then $\mathrm{x}_{\mathrm{tran}}^{0}$ is the sum of the product of those sectors at pre-disaster level, and $x_{\text{tran}}^{*(t)}$ is the product of those sectors at time t during recovery, obtained from the vectors of productive capacity, $\mathbf{x}^0$ and $\mathbf{x}^{*(\mathrm{t})}$, respectively.

3.1.2.3 Recovery

Decisions to return to pre-disaster conditions can be complex and varied. Here, we have assumed a way of adapting to a condition of balanced production and demand. That is, we pursue a partial equilibrium for productive capacities at each time period – through the rationing scheme– and then follow a long-term growth tendency towards the pre-disaster level of production – through the reconstruction efforts.

It should be remembered that the recovery process implicates the repair and/or replacement of the damaged capital stock and households. During this process, production capacity increases both through local production and through imports allocated to *reconstruction demand*.

Then, the productive capacity of each industry for the next period incorporates the rebuilt capacity of the previous period:

$$x_{cap}^{t+1}(i) = x_{cap}^{t}(i) + g\left\{\left[m^t(i) + \left(x_{tp}^t(i) - \sum_{j=1}^{n} a_{ij} x_{tp}^t(j)\right)\right] * \left[f_{cap}^t(i) ./ \left(\sum \boldsymbol{f}_k^0 + \boldsymbol{f}_{rec}^t\right)\right]\right\} \tag{3.15}$$

Where g is the generic function that encloses the relation capital-production.

Note that the proportion of affected capital –the EAV– changes for each sector as follows:

$$\gamma_i^t - \gamma_i^{t+1} = \frac{\left\{\left[m^t(i) + \left(x_{tp}^t(i) - \sum_{j=1}^{n} a_{ij} x_{tp}^t(j)\right)\right] * \left[f_{cap}^t(i) ./ \left(\sum \boldsymbol{f}_k^0 + \boldsymbol{f}_{rec}^t\right)\right]\right\}}{\boldsymbol{f}_{rec}^0} \tag{3.16}$$

This new level of production is compared with the level of labour capacity at the next time-step. Then, the process described above is repeated until an equilibrated economy at the pre-disaster production level is reached.

The recovery mechanism is driven by several variables. Once the proportional reduction in production has been determined -for each industry- the drivers can be found in both supply and demand side of the economy. However, as IO is basically a demand-driven model, is the different demand categories which drive the recovery. While restoration in supply capacity allows to cover that demand. The process is as follows:

First, the intermediate demand has to be satisfied. The rationing scheme searches for a temporal equilibrium, equals to the minimum proportion of affected sector as inputs for other industries. The decreased amount in demand has to be adjusted for all industries, so that some productive capacity is freed to satisfy part of the final demand, which includes final demand for reconstruction or reinvestment in restoring capital. Then, the partial satisfaction of the recovery demand is transformed in regenerated productive capacity.

On the other hand, the final demand categories pull the economy towards the pre-disaster level. The households' demand recovers along time. These are the drivers of recovery, but it is constrained to the recovery of productive capacity of both, industrial and human capital. The recovery of labour productive capacity is exogenously modelled. There are several ways to model it, but it basically refers to the proportional increase in production capacity as the affected labour restore its capacity for working. The recovery for productive capacity of industrial capital is already described, but there is another element that helps to the recovery. It is the products from abroad the impacted region. The flood footprint model considers the contribution of imports to the recovery process, proportionally allocated for all demand categories.

The evolution of driver variables follows a positive tendency with decreasing growth rate. The demand categories tend to be fulfilled by the productive capacity, while recovery demand and imports for reconstruction decrease until reaching zero. The recovery process may continue some periods more after the pre-disaster production level is reached, but some imbalances in markets may remain.

3.2 Flood Footprint modelling outcomes

The flood footprint model provides us with the outcomes of diverse economic variables over the course of the recovery process. All results are provided at each time-step during restoration and at a disaggregation level of 46 industrial sectors. The time that each variable and sector requires to achieve its pre-disaster level is, likewise, provided by the model.

Results of the *direct* and *indirect damages* constitute the principal outcomes of the model.

The *direct damages* account for the value and the proportion of the damages to the physical infrastructure, both to industrial and residential capital. To determine these, we construct the EAV with the proportion of damage to the capital stock as the cost of reconstruction. The model, in turn, translates the damage from this *stock variable* into damages to productivity, a *flow variable*.

The *indirect damages* account, period by period, for non-realised production owing to constraints in both productivity and demand, i.e., the cascading effects from the *direct damages*.

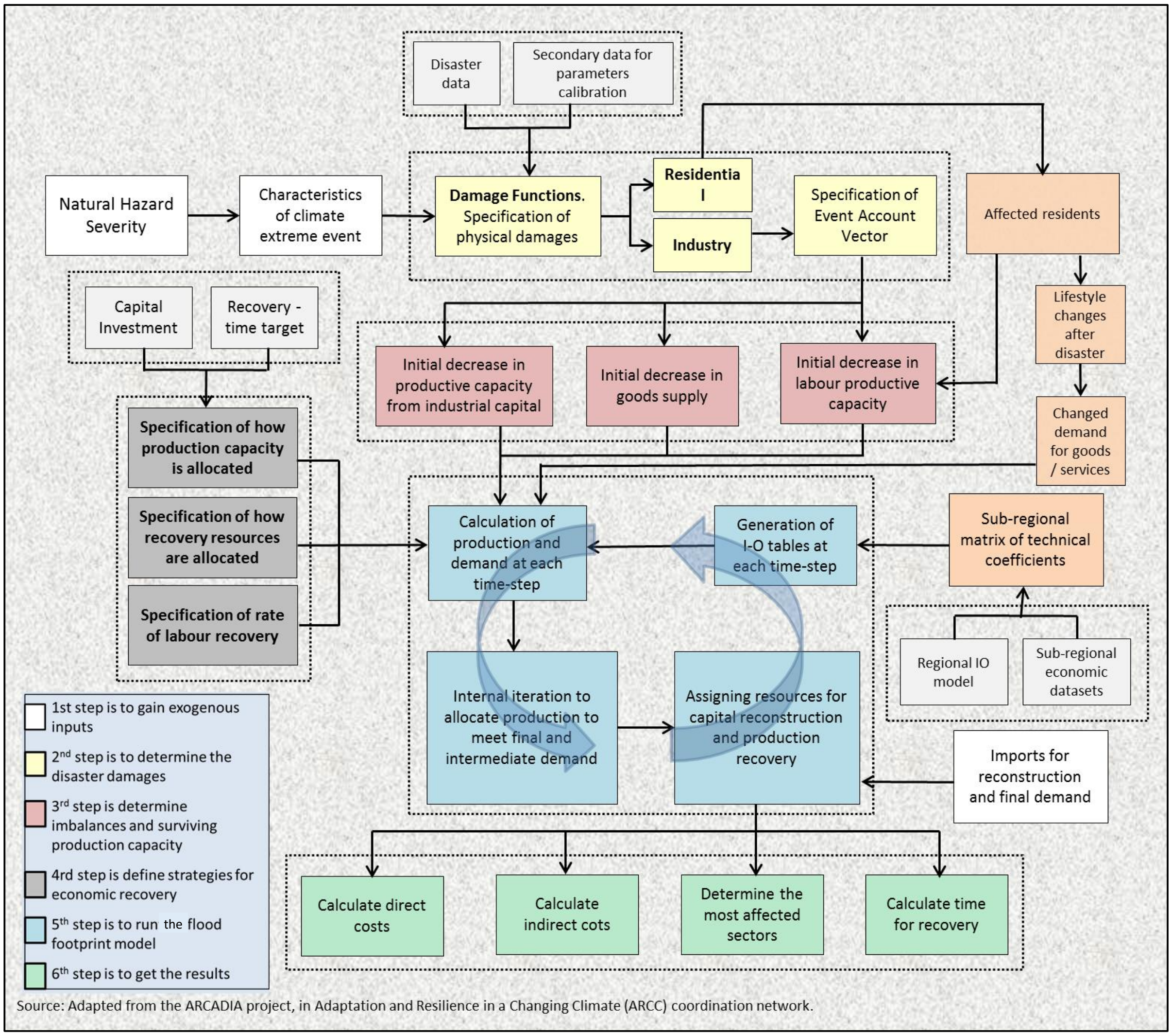
The model delivers the dynamics of recovery for other variables, such as the restoration in industrial productive capacity; labour productive capacity; the contribution of imports to the economy during the recovery process; and final demand, as the restoration of levels of consumption in each category.

It should be considered that the trajectories of the variables' recoveries are influenced by the assumptions and decisions considered for reconstruction, such as the establishment of the rationing scheme. On the other hand, a sensitivity analysis of the parameters is performed to obtain robust results and to determine how the results are influenced by changes in the parameters.

3.3 Flowchart for flood footprint modelling

The figure below summarises the workflow (modelling process) for estimating the total cumulative economic impact of a flooding event, or the flood footprint. The figure has been adapted from the model that serves as the base for the flood footprint, i.e. the Adaptive Regional IO model (ARIO). The entire process can be summarised in six steps. Each step illustrates the contribution made in this research to the mentioned model. The aim of recovery is resuming the production level at pre-disaster condition.

Figure 3.1 Modelling process for Flood Footprint appraisal



Source: Adapted from the ARCADIA project, in Adaptation and Resilience in a Changing Climate (ARCC) network.

Step 1 is obtaining exogenous inputs to the flood footprint model. The white boxes in the figure above detail the input data and factor required. As each phenomenon is different, the data gathering is an entirely contribution of this thesis for each of the case studies. The process is different in each case, as they cover different regions, scales, and modelling needs.

- Natural hazard severity and characteristics of the disaster (top left white boxes) define the study event by employing this model framework. This can potentially also link with global / regional climatic change scenarios to model precipitation levels, etc. for future hazards (e.g. 1/100 years flooding or 1/1000 years flooding event).

- Investment/Capital Matrix and policy intervention recovery (top-middle white boxes) describe external factors that will be influencing recovery patterns, for example, governmental activities in extra investment for reconstruction. The capital matrix determines investments needed to restore production capacity to pre-disaster levels. One can model the differences (e.g. costs and benefits) of economic losses *with* versus *without* any adaptation plans for future events in a city or country.

- Damage database and secondary information for parameters calibration (top white boxes) are necessary information that constitute the specification of the physical damages. When assessing past events, most of this information should be available from insurance or reinsurance companies. Other data sources for past events can be governmental reports (e.g. UK Environmental Agency reports or local city council reports for extreme events), and independent research reports. For future events, hydrological or flooding engineering models can be built into this damage database. For example, flood inundation models would be able to predict duration and velocity of a flood event with inputs from predicted precipitation levels of climatic change models.

- The regional IO model (right middle white box) provides annual input-output tables for the flood footprint model; and a sub-regional economic dataset allows us to construct the sub-regional IO tables. Most input-output tables are compiled and published at national level. Some cities have city-level input-output tables. If there are no regional / city specific input-output tables, statistical techniques (e.g. location quotients) can be applied to obtain such table by assuming similar production structure as national average. In recent years, multi-regional input-output (MRIO) models have been developed and extensively used. Utilisation of MRIO models in estimating economic losses in post-disaster situations is limited and requires careful design and implementation in terms of estimating impacts to international / intraregional supply chains.

Step 2 is to determine the damages (in economic terms) from the destruction in residential and industry capital (yellow boxes). The contribution in this step extends from the previous step. The codification of the disaster information in economic damage, and more specifically, in the proportion of industrial capital damaged for each sector, has been refined along the research and modelling process. In the first case study, the data was gathered from a government agency report. However, following case studies incorporated the use of damage functions, which provides with the monetary valuation of the disaster's destruction. So, the contribution was to adapt the damage functions and obtain the values of the Event Account Vector. The process is as follows:

- After damage data is obtained from various sources, damage functions are constructed. Capital damage is categorised as industrial capital and residential capital. During recovery, both capitals will be repaired or replaced, but only industrial capital damages would affect economic productivity performance. In most cases, damages are reported in monetary terms. This needs to be converted to a proportion of damage in industrial capital stock. This information is the input to construct the EAV.

- Damages to residential capital affect the economy in different ways (light orange boxes): from the production side, they affect the availability of labour force. In addition, from the demand side, the consumption of the affected labour would change during the aftermath.

- *Household Consumption Behaviour*: During the disaster event and the recovery period, households' demand for goods and services can be changed. For example, households may keep same consumption level for food and clothes (or basic needs), but reduce the consumption of luxury goods and services. Along with the recovery, their consumption level for luxury goods and services can resume to pre-disaster level. Again, there is a lack of studies in quantifying the relationship between consumption levels and disaster severity and recovery for different types of hazards. Thus, potential links with psychological studies could be an option here. For the case studies in this thesis, the consumption behaviour in the aftermath is exogenously modelled. Several assumptions on the recovery path have been tested to account for different situations. The analysis showed that the results are not highly sensible to changes in households' consumption.

Step 3 is to define the initial economic imbalances and the surviving production capacity after the disaster (red boxes). The contribution in this modelling step is more empirical, in the accounting of imbalances. Some adjustments had to be done in the parameters for changes in households' consumptions after the disaster. For example, the recovery path for consumption, and the ratio of recovery for each period. In particular, we consider an s-shape recovery curve which indicates a small recovery in the beginning of the disaster aftermath, with a high recovery afterwards, to finally stabilise in the end of the recovery process. Likewise, parameters for labour constraints where calibrated through a sensitivity analysis, as data related with labour constraints is very scarce.

- *Labour constraints*: From the damage dataset, residential damage and the number of affected households (or population) can be obtained. This information can be used to estimate the amount of labour which would be either unavailable or delayed in travel to work (as a production constraint during economic recovery period). However, there is a lack of studies in determining the relationship between residential capital damage and labour delays, and some assumptions have to be made to model an exogenously labour recovery path. For some of the case studies in this thesis the data on labour constraints is inferred from secondary data (as from reports of government or social organisations, or from the news). The information is cross-referenced with damages in some sectors that may affect labour productivity, such as residential damage and damages in transport sectors.

- Remaining industrial capital and labour availability after a disaster will both affect the remaining production capacity. Minimum of the proportion of these two productive factors can be used to determine the remaining production capacity for economic recovery, as described in more details in the IO model description (see equation (3.11)).

Step 4 is to define the strategies for economic recovery along the disaster aftermath (grey boxes). One of the main contributions of the thesis is in this step of the modelling. In particular, it was incorporated the capital matrix that show the distribution of recovery demand that have to be covered to restore the destroyed capital. Likewise, in the third analytical chapter, about the case study for the Windstorm Xhynthia, and the 2009 Floods in Central Europe, it was incorporated in the model the possibility of recovery planning.

- The flood footprint model allows for some characteristics of recovery planning. For instance, it can be modelled the recovery path for industrial capital. This accounts for the capital investment that is needed each period to replace the value of the lost capital from the disaster in a targeted period. For these cases, the model has shown that even when the capital is replaced, the economy may take it longer for recovery, as some imbalances from the initial shock may remain longer.

- The rationing scheme is set up to determine priority levels of resources allocations. Specific recovery patterns are decided for labour recovery patterns, as well.

- An exogenous recovery path of labour, based on the overall scale of the extreme events, is applied. We assume every labourer works for 8 × 22 hours per month. If the amount of extra hours for each labourer that is spent on travelling in month t post-disaster replaces working hours and is captured by o_i, and the percentage of labour affected is p_i, then the relative percentage of labour loss in the month is identified by $p_i \, * \, o_i \, / \, (8 \, \times \, 22)$.

Step 5 is to configure the flood footprint model and compute the recovery of the economy. The four blue boxes in the figure above show a recovery loop. This step represents the main methodological contribution of the thesis. The flood footprint model was extended from the single-regional analysis to consider multiple regions analysis and finally to develop the multiregional flood footprint model (section 3.5).

- After obtaining the regional technical coefficients matrix, the values for the regional input-output tables at each time-step are obtained directly. One can argue that such technical matrix can be changed after a disaster event due to new industrial relationships. However, in this thesis, we assume the same production technology and patterns throughout the recovery period. This assumption can only be reasonable if any disaster is not severe enough to cause structural transformation in production structure in a short period, say within a few years. The extreme severe events, such as Hurricane Katrina hitting the Western coast of the United States in 2005, or the Fukushima nuclear incident produced by the huge tsunami affecting Japan in 2011, would require careful re-design of the modelling framework in terms of post-disaster changes in production structure when estimation of economic losses take place.

- Production capacity and final demand recovery is calculated at each time step.

- Calculated production capacity will be used as available resources to be allocated at next time point. The rationing scheme is applied to allocate the production capacity among intermediate demand and all final demand users.

- At every time-step, some damaged capital is recovered, and more production capacity is gained. The model will be looped until the pre-disaster production condition is met.

- In the flood footprint modelling, it is assumed that imports contribute in some extent to the recovery process and to the supply of final consumption. The amount of imports may rely on the condition of transportation sectors, as stated in section 3.1.2.2. In modelling practice, one would assume that the availability of required inputs from import is infinite, but constrained by the *transportation capacity* (lower-right white box).

Step 6 is to get the results from the flood footprint model. Four major results can be obtained, as shown in green boxes at the bottom of the figure above. This thesis contributes in carrying out a sensitivity analysis upon all model parameters, and presents the result for the main outcome variables. This is presented in the results section of each of the case studies' chapters.

- Direct economic loss (by sector and by region) is computed as the value added needed to replace the proportion of industrial capital that was destroyed by the disaster.

- Indirect economic loss (by sector and by region) is computed as the accumulation at each time-step, along the recovery time, of the difference between recovered production capacity and the pre-disaster condition.

- Total economic loss, or flood footprint, is the sum of direct and indirect economic losses.

- The time taken for fully recovery of the economy.

- Results can be illustrated by sectors and regions (for the multiple single-regional and the multiregional case studies analysis).

3.4 Standard Flood Footprint model for multiple regions

This section describes the modelling extension to apply the single-regional analysis to multiple regions. It must be noted, however, that these multiple regions do not directly interact each other. The interaction is indirectly given by the products that each region imports from the 'outer world', but without determining the origin of those products, as in the original single-regional flood footprint model. In short, the multiple-regions analysis applies the single-regional flood footprint model to all the regions affected by a given disaster.

An important methodological advance is given by the incorporation of the capital matrix, an element from IO modelling that provides consistency in transiting from flow variables (production) values towards stock variables values (capital stock).

This version is applied to the case studies of the 2009 floods in Central Europe, and the Xynthia Windstorm affecting Europe in 2010.

Applying the standard flood footprint model to multiple regions implies the appraisal by region. This is explicitly stated with the superscript in the model equations. Therefore, the superscript r denotes the region of analysis.

Again, we depart form the basic equation as in equation (3.42) that contains all the intermediate transactions and labour requirements per sector, per region:

$$\begin{bmatrix} \mathbf{A}^{\mathrm{r}} & \mathbf{f}^{\mathrm{r}}/l^{r} \\ \mathbf{l}'^{\mathrm{r}} & 0 \end{bmatrix} \begin{pmatrix} \mathbf{x}^{\mathrm{r}} \\ l^{r} \end{pmatrix} = \begin{pmatrix} \mathbf{x}^{\mathrm{r}} \\ l^{r} \end{pmatrix} \quad (3.17)$$

Then, the total production capacity in each region, after considering the constraints from industrial capital and labour force, is analogous to the equation (3.11):

$$\mathbf{x}_{\mathrm{tp}}^{\mathrm{r,t}} = \min\left\{\mathbf{x}_{\mathrm{cap}}^{\mathrm{r,t}}, \mathbf{x}_{\mathrm{l}}^{\mathrm{r,t}}\right\} \quad (3.18)$$

And the total final demand each period along the aftermath is analogous to the equation (3.10), so that for each industry in region r, the total demand is:

$$\mathrm{x}_{\mathrm{td}}^{\mathrm{r,t}}(\mathrm{i}) = \sum_{\mathrm{j=1}}^{\mathrm{n}} \mathrm{a}_{\mathrm{ij}}^{\mathrm{r}} \mathrm{x}_{\mathrm{td}}^{\mathrm{r,t}}(\mathrm{j}) + \mathrm{f}^{\mathrm{r,t}}(\mathrm{i}) \quad (3.19)$$

For the recovery process, the concept of using a capital matrix to translate the investment in reconstruction demand into the increase of productive capacity from industrial sectors was incorporated. This is detailed in the next section.

3.4.1 Recovery process and the capital matrix

This section describes the incorporation of the *capital matrix* to the analytical framework of the flood footprint to achieve a methodologically consistent transformation from capital investment to productive capacity. The use of the capital matrix in the impact analysis of post-disaster economies is originally introduced and developed by Albert Steenge within (Triple E Consulting, 2014). He considers the investment in restoration as an exogenous variable, allowing for recovery planning. In this chapter, the *capital matrix* is adapted within the original flood footprint framework; where the recovery investment is allocated according to the share of demand for reconstruction related with the other categories of final demand. As in the single-regional flood footprint, it is assumed that the allocation of surviving production is distributed to the different categories of final demand once the intermediate demand is satisfied.

The *capital matrix* is traditionally used in IO analysis to simulate the economic growth by capital accumulation. A capital matrix, $\boldsymbol{K}$, is a square matrix where each element, $k(i,j)$, represents the amount of capital produced by sector i to increase output capacity of sector j by one unit. Therefore, the elements of column j represent the products needed from all sectors to produce an extra unit of product in that sector (Miller & Blair, 2009).

It should be remembered that the recovery process requires the repair and/or replacement of the damaged capital stock and households. During this process, the production capacity increases through both local production and imports allocated to the *reconstruction investment*. Note that the reconstruction of households is through the consumption of final products to the reconstruction sectors.

The capital investment for reconstruction is computed as the share of the reconstruction demand among all final demand categories, multiplied by the remaining production after satisfying the intermediate demand. It must be noted that here, the investment in capital restoration entails both, the requirements of capital by industry disclosed in the capital matrix, $\mathbf{K}^{\mathrm{r}}$, and the amount of productive capacity that is added to the next time, $\Delta\mathbf{x}_{\mathrm{cap}}^{\mathrm{r,t}}$, as a result of the capital investment in this period, $\mathbf{K}^{\mathrm{r}} * \Delta\mathbf{x}_{\mathrm{cap}}^{\mathrm{r,t}}$:

$$\mathbf{K}^{\mathrm{r}} * \Delta\mathbf{x}_{\mathrm{cap}}^{\mathrm{r,t}} = (\mathbf{x}_{\mathrm{tp}}^{\mathrm{r,t}} - \mathbf{A}\mathbf{x}_{\mathrm{td}}^{\mathrm{r,t}}) * (\mathbf{f}_{\mathrm{cap}}^{\mathrm{r,t}}./\mathbf{f}_{\mathrm{td}}^{\mathrm{r,t}}) \tag{3.20}$$

Similarly, the share of imports that are invested in reconstruction capital can be expressed, to estimate their contribution to increase the production capacity during the reconstruction process. Once the amount of imports designated to capital investment is determined as in equation (3.45), the restoration in productive capacity from imports, $\Delta\mathbf{x}_{\mathrm{m}}^{\mathrm{r,t}}$ can be easily obtained.

$$\mathbf{K}^{\mathrm{r}} * \Delta\mathbf{x}_{\mathrm{m}}^{\mathrm{r,t}} = \mathbf{m}^{\mathrm{r,t}} * \left[\mathbf{f}_{\mathrm{cap}}^{\mathrm{r,t}} \cdot\Big/ \left(\sum_{k} \mathbf{f}_{\mathrm{k}}^{\mathrm{r,0}} + \mathbf{f}_{\mathrm{rec}}^{\mathrm{r,t}}\right)\right] \tag{3.21}$$

Remember that the summation $\sum_{k} \mathbf{f}_{\mathrm{k}}^{\mathrm{r,0}}$ represents the total final demand of all k pre-disaster categories (households, government, capital, exports).

Then, the total investment in capital restoration each period is:

$$\mathbf{K}^{\mathrm{r}} * \Delta\mathbf{x}^{\mathrm{r,t}} = \mathbf{K}^{\mathrm{r}} * (\Delta\mathbf{x}_{\mathrm{tp}}^{\mathrm{r,t}} + \Delta\mathbf{x}_{\mathrm{m}}^{\mathrm{r,t}}) \tag{3.22}$$

Multiplying by the inverse of the *capital matrix* provides the industrial productive capacity that is added for the next period, $\Delta\mathbf{x}^{\mathrm{r,t}} = \Delta\mathbf{x}_{\mathrm{tp}}^{\mathrm{r,t}} + \Delta\mathbf{x}_{\mathrm{m}}^{\mathrm{r,t}}$.

Thus, for the next period, the production possibilities from industrial capacity is given by the following expression:

$$\mathbf{x}_{\mathrm{cap}}^{\mathrm{r,t+1}} = \mathbf{x}_{\mathrm{cap}}^{\mathrm{r,t}} + \Delta\mathbf{x}^{\mathrm{r,t}} \tag{3.23}$$

This allows to reformulate the function of vector $\mathbf{f}_{\mathrm{rec}}^{\mathrm{r,t}}$ in terms of a Leontief capital matrix $\mathbf{K}^{\mathrm{r}}$. Substituting the term ($\Delta\mathbf{x}^{\mathrm{r,t}}$) in Equation (3.23), in terms of the capital matrix, gives the total demand requested by the economy in each period during the recovery process:

$$\mathbf{x}_{\mathrm{td}}^{\mathrm{r,t}} = \mathbf{A}^{\mathrm{r}}\mathbf{x}_{\mathrm{td}}^{\mathrm{r,t}} + \sum_{k} \mathbf{f}_{\mathrm{k}}^{\mathrm{r,0}} + \mathbf{f}_{\mathrm{hd}}^{\mathrm{t}} + \mathbf{K}^{\mathrm{r}}\Delta\mathbf{x}^{\mathbf{r,t}} \tag{3.24}$$

Note that there is a trade-off in the use of resources between the different categories of demand: intermediate consumption, demand for final goods, households' reconstruction and demand for industrial reconstruction.

The expression above represents a specific prioritisation strategy, where recovery demand is attended only after intermediate demand is satisfied, with a trade-off among other final demand categories. However, the model is flexible enough to consider different allocation and recovery pathways.

3.4.2 Total Flood Footprint for multiple regions

Finally, the total flood footprint of the event is considered as the sum of the flood footprint of all the affected regions:

$$\mathbf{ff} = \sum_{r} (\mathbf{va}_{\mathrm{dir}}^{\mathrm{r}} + \mathbf{va}_{\mathrm{ind}}^{\mathrm{r}}) = \sum_{r} \left[\mathbf{f}_{\mathrm{rec}}^{\mathrm{r},0} + \left(T^{r} * \mathbf{x}^{\mathrm{r},0} - \sum_{\mathrm{t}} \mathbf{x}_{\mathrm{tp}}^{\mathrm{r,t}} \right) \right] \tag{3.25}$$

Where T^{r}Is the time calculated for recovery in each of the regions.

3.5 Methodology for the multi-regional Flood Footprint model

This section presents the multi-regional version of the flood footprint model, which incorporates a Multi-Regional IO (MRIO) table to account for the effects of changes in the trade between the affected country and other countries, as a result of production losses. This represents the most complete version of the flood footprint model, as it accounts for affectations to interlinked economies throughout international trade. This version is used for flood footprint appraisal of a flooding projection in the city of Rotterdam, The Netherlands. The analysis' results are presented in Chapter 6.

To incorporate the multiregional dimension to the equations nomenclature, let the superscript r refers to the region and goes before the superscript of time t. In case it is needed to indicate origin and destination-regions, this will be indicated by either the superscript r or s (as in the expression $z^{rs,t}$) where the superscript to the left indicates the region of origin and the superscript to the right indicates the destination region. For the case of final demand, the subscript k indicates the category in which the final demand is consumed, which may take the values: 1 (household demand), 2 (government consumption), 3 (capital investment), and 4 (exports). When considering the industry, this subscript will be located to the right of the industry subscript (as in the expression $f_{i,k}$). Finally, the flooded region is distinguished by an asterisk next to the region-superscript (as in the expression x^{r^*}).

The MRIO tables present the inter-industrial transactions within the regional economy, r, and with the rest of the regions. Furthermore, the tables describe the flow of final products from region r to satisfy local and interregional final demand. Figure 3.2 presents an example of a MRIO table with three regions and two same sectors in each region.

Figure 3.2 MRIO table for three regions and two sectors each

	Interregional interindustry consumption	**Interregional final demand**	**Total output**
	$\begin{matrix} \begin{bmatrix} z^{11}_{11} & z^{11}_{12} \\ z^{11}_{21} & z^{11}_{22} \end{bmatrix} & \begin{bmatrix} z^{12}_{11} & z^{12}_{12} \\ z^{12}_{21} & z^{12}_{22} \end{bmatrix} & \begin{bmatrix} z^{13}_{11} & z^{13}_{12} \\ z^{13}_{21} & z^{13}_{22} \end{bmatrix} \\ \begin{bmatrix} z^{21}_{11} & z^{21}_{12} \\ z^{21}_{21} & z^{21}_{22} \end{bmatrix} & \begin{bmatrix} z^{22}_{11} & z^{22}_{12} \\ z^{22}_{21} & z^{22}_{22} \end{bmatrix} & \begin{bmatrix} z^{23}_{11} & z^{23}_{12} \\ z^{23}_{21} & z^{23}_{22} \end{bmatrix} \\ \begin{bmatrix} z^{31}_{11} & z^{31}_{12} \\ z^{31}_{21} & z^{31}_{22} \end{bmatrix} & \begin{bmatrix} z^{32}_{11} & z^{32}_{12} \\ z^{32}_{21} & z^{32}_{22} \end{bmatrix} & \begin{bmatrix} z^{33}_{11} & z^{33}_{12} \\ z^{33}_{21} & z^{33}_{22} \end{bmatrix} \end{matrix}$	$\begin{matrix} \begin{bmatrix} f^{11}_{1} & f^{12}_{1} & f^{13}_{1} \\ f^{11}_{2} & f^{12}_{2} & f^{13}_{2} \end{bmatrix} \\ \begin{bmatrix} f^{21}_{1} & f^{22}_{1} & f^{23}_{1} \\ f^{21}_{2} & f^{22}_{2} & f^{23}_{2} \end{bmatrix} \\ \begin{bmatrix} f^{31}_{1} & f^{32}_{1} & f^{33}_{1} \\ f^{31}_{2} & f^{32}_{2} & f^{33}_{2} \end{bmatrix} \end{matrix}$	$\begin{matrix} \begin{bmatrix} x^{1}_{1} \\ x^{1}_{2} \end{bmatrix} \\ \begin{bmatrix} x^{2}_{1} \\ x^{2}_{2} \end{bmatrix} \\ \begin{bmatrix} x^{3}_{1} \\ x^{3}_{2} \end{bmatrix} \end{matrix}$
Value added	$[va^1_1 \quad va^1_2] \quad [va^2_1 \quad va^2_2] \quad [va^3_1 \quad va^3_2]$		
Total inputs	$[x^1_1 \quad x^1_2] \quad [x^2_1 \quad x^2_2] \quad [x^3_1 \quad x^3_2]$		

Source: Based on Timmer et al. (2015).

Let us now to reintroduce the mathematics of the MRIO, following the description in section 2.6.2. The general structure that describes the MRIO model, as in equation (2.71) (reproduced here), is:

$$\mathbf{x} = \mathbf{CAx} + \mathbf{Cf} \tag{3.26}$$

Note that the elements in Equation (3.26) contains the information for all regions. To avoid confusions, we redefine the terms, so that $\mathbf{CA} = \mathbf{A^R}$, $\mathbf{Cf} = \tilde{\mathbf{f}}\mathbf{i} = \mathbf{f^R}$, where $\mathbf{i}$ is a *summation* vector (a vector of ones) with same number of elements as columns in matrix $\tilde{\mathbf{f}}$. $\mathbf{x^R}$ is the production (transposed) vector for all regions, i.e. $\mathbf{x^R} = [\mathbf{x^1}, \mathbf{x^2}, \dots, \mathbf{x^r}, \dots, \mathbf{x^q}]$ where q is the number of regions, and the superscript R indicates an element that encloses the information for all regions. Note that all the elements contain the information of all sectors of the correspondent region.

The model now looks similar to the original single-regional IO:

$$\mathbf{x^R} = \mathbf{A^R x^R} + \mathbf{f}^{R} \tag{3.27}$$

Hereafter, for simplicity, let us assume all regions have the same number of sector. Therefore, vector $\mathbf{x^R}$ and vector $\mathbf{f^R}$ have dimensions of $(n * q)x1$, and the matrix $\mathbf{A^R}$ has a dimension

$(n * q)x(n * q)$, so that the resulting vector $\mathbf{A^R x^R}$ has a dimension $(n * q)x1$. Here, n is the total number of industries in each region, and q is the total number of regions.

When expanded, this can be written as:

$$\begin{bmatrix} \mathbf{x^1} \\ \vdots \\ \mathbf{x^r} \\ \vdots \\ \mathbf{x^R} \end{bmatrix} = \begin{bmatrix} \mathbf{A^{11}} & \dots & \mathbf{A^{1R}} \\ \vdots & \mathbf{A^{rs}} & \vdots \\ \mathbf{A^{r1}} & \mathbf{A^{rr}} & \mathbf{A^{rR}} \\ \vdots & \ddots & \vdots \\ \mathbf{A^{R1}} & \dots & \mathbf{A^{RR}} \end{bmatrix} \begin{bmatrix} \mathbf{x^1} \\ \vdots \\ \mathbf{x^r} \\ \vdots \\ \mathbf{x^R} \end{bmatrix} + \begin{bmatrix} \mathbf{f^{11}} & \dots & \mathbf{f^{1R}} \\ \vdots & \mathbf{f^{rs}} & \vdots \\ \mathbf{f^{r1}} & \mathbf{f^{rr}} & \mathbf{f^{rR}} \\ \vdots & \ddots & \vdots \\ \mathbf{f^{R1}} & \dots & \mathbf{f^{RR}} \end{bmatrix} \begin{bmatrix} \mathbf{I} \\ \vdots \\ \mathbf{I} \\ \vdots \\ \mathbf{I} \end{bmatrix} \qquad (3.28)$$

Where $\mathbf{x^r}$ is the vector of production in region r (with dimension $nx1$). $\mathbf{A^{rs}}$ is the matrix $\mathbf{\hat{c}^{rs} A^r}$ in equation (2.70) that indicates the technical proportion of products produced in region s needed for production in region r when $s \neq r$; and the regional technical coefficients matrix $\mathbf{A^{rr}}$ when $s = r$ (with dimension nxn). $\mathbf{f^{rs}}$ is the vector of total final demand in region s for products from region r when $s \neq r$; and the local final demand, $\mathbf{f^{rr}}$**,** when $r = s$ (of dimension $nx1$). Therefore, the production of region r is:

$$\mathbf{x^r} = \sum_{\mathbf{s}} \mathbf{A^{rs}\, x^s} + \sum_{\mathbf{s}} \mathbf{f^{rs}} \qquad (3.29)$$

Equation (3.29) expresses the requirements of products of region r from all other regions, for both intermediate and final demand. Note that the summation operators run over regions, which indicates the summation of vectors.

The (transposed) vector of technical coefficients of labour in the multiregional version of the *basic equation* (equation (3.30)) contains the labour data for all sectors for all regions:

$$\mathbf{l^{R\prime}} = \left[\left(\frac{l_1^1}{x_1^1}, \frac{l_2^1}{x_2^1}, \dots, \frac{l_i^1}{x_i^1}, \dots, \frac{l_n^1}{x_n^1}\right), \dots, \left(\frac{l_1^r}{x_1^r}, \frac{l_2^r}{x_2^r}, \dots, \frac{l_i^r}{x_i^r}, \dots, \frac{l_n^r}{x_n^r}\right), \dots, \left(\frac{l_1^q}{x_1^q}, \frac{l_2^q}{x_2^q}, \dots, \frac{l_i^q}{x_i^q}, \dots, \frac{l_n^q}{x_n^q}\right)\right] \qquad (3.30)$$

Where the element $\left[\frac{l_i^r}{x_i^r}\right]$ indicates the technical proportion of labour required in region r in industry i to produce one unit of product in the same region and industry.

From this point, the model proceeds in an analogous way as the single-regional flood footprint model described at the beginning of this section.

3.5.1 Production constraints

The development of the multiregional version of the model allows for the assessment of different climate extreme events happening at the same time in different regions. This is possible thanks to the multiregional EAV ($\boldsymbol{\gamma}_{\mathbf{cap}}^{\mathbf{R,t}}$) and the analogous element to consider constraints in labour productive capacity ($\boldsymbol{\gamma}_{\mathbf{l}}^{\mathbf{R,t}}$). For simplicity, this case examines a single climate extreme event in one region (r).

3.5.2 Labour productivity constraints

As in equation (3.4), the productive capacity given the labour constraints at each time step is:

$$\mathbf{x}_{\mathrm{l}}^{\mathrm{R,t}} = \left[\left(\mathbf{i} - \boldsymbol{\gamma}_{\mathbf{l}}^{\mathbf{R,t}}\right)\right].* \mathbf{x}^{\mathbf{R,0}} \tag{3.31}$$

Where the term $\boldsymbol{\gamma}_{\mathbf{l}}^{\mathbf{R,t}}$ is a vector of dimension $(n * r)x1$ and contains the proportion of affected productive capacity owing to labour constraints in sector i in region r for each time step of the recovery period. The element $\mathbf{i}$ is a vector of ones the same size as vector $\boldsymbol{\gamma}_{\mathbf{l}}^{\mathbf{t}}$. The term $\mathbf{x}^{\mathbf{R,0}}$ is the vector of production in all sectors in all regions prior to the disaster.

$$\begin{aligned}&\boldsymbol{\gamma}_{\mathbf{l}}^{\prime\mathbf{R,t}}\\ &= \left[\left(0_{l,1}, \dots, 0_{l,i}, \dots, 0_{l,i}\right)^{\mathbf{1}}, \dots, \left(\gamma_{l,1}, \dots, \gamma_{l,i}, \dots, \gamma_{l,n}\right)^{\boldsymbol{r}^*}, \dots, \left(0_{l,1}, \dots, 0_{l,i}, \dots, 0_{l,n}\right)^{\mathbf{q}}\right]^{\boldsymbol{t}}\end{aligned} \tag{3.32}$$

The vectors in parenthesis indicate the damage by sector in each region, such that for non-flooded regions the damage from labour constraints is zero.

3.5.3 Capital production constraints

Similar to labour constraints, the multiregional EAV ($\boldsymbol{\gamma}_{\mathbf{cap}}^{\mathbf{R,t}}$) is a vector of dimension $(n * r)x1$ that contains the proportions of affected industrial capital in each sector in each affected region, at the period t. Assuming just region r has been affected by a natural disaster, the multiregional EAV will account for the reduced production capacity due to damage in industrial capital of region r^*, and will contain zeros in the rest of the elements, as in equation (3.33) (note the presentation is in row form).

$$\boldsymbol{\gamma}_{\mathbf{cap}}^{\mathbf{R,t}} = \begin{bmatrix} \left(0_{cap,1}, \dots, 0_{cap,i}, \dots, 0_{cap,n}\right)^{\mathbf{1}}, \dots, \\ \left(\gamma_{cap,1}, \dots, \gamma_{cap,i}, \dots, \gamma_{cap,n}\right)^{\boldsymbol{r}^*}, \dots, \left(0_{cap,1}, \dots, 0_{cap,i}, \dots, 0_{cap,n}\right)^{\mathbf{q}} \end{bmatrix}^{\boldsymbol{t}} \tag{3.33}$$

As in the case of labour constraints, the vector of available production capacity of industrial capital in time t for all industries and all regions, is given in a transposed way by the equation (3.34). This is a (transposed) vector of dimension $(n * q)x1$ and indicates the constraints in the affected region(s) wherein the elements have a positive value ($\gamma_{\mathrm{i}}^{\mathrm{r,t}} > 0$).

$$\mathbf{x}_{\mathrm{cap}}^{\mathrm{R,t}} = \left(\mathbf{i} - \boldsymbol{\gamma}_{\mathbf{cap}}^{\mathbf{R}}\right).* \mathbf{x}^{\mathbf{R,0}}$$
$$= \left[(\mathrm{x}_1, \dots, \mathrm{x}_\mathrm{n})^1, \dots, \left((1-\gamma_1)x_1, \dots, (1-\gamma_\mathrm{n})\mathrm{x}_\mathrm{n}\right)^{r^*}, \dots (\mathrm{x}_1, \dots, \mathrm{x}_\mathrm{n})^q\right]^t \tag{3.34}$$

3.5.4 Changes in final demand

The changes in final demand for the affected region are modelled as in the single-regional model, while the rest of the regions remain unchanged. The final demand in the affected region changes by two factors that act in opposite directions. First, behavioural changes in households' consumption reduces the local demand for those non-basic products/industries and remains the same for the industries providing basic goods[19]. Secondly, the final demand increases in those sectors locally involved in the reconstruction process.

3.5.5 Post-disaster recovery process

The process to determine the production capacity in the aftermath of a disaster works in the same way as in the single-region model for the affected region. Then, the productive capacity of industrial capital is compared with the productive capacity of labour to determine the economy's capacity, as in equation (3.11).

Then, the rationing scheme runs in the same way, as in the single-regional model, to determine any possible bottleneck in the supply chain, as in section 3.1.2.1. After this, the total production capacity of the affected region is determined, and together with the adapted final demand determine the level of total demand in the affected region each period t:

$$\mathbf{x}_{\mathrm{td}}^{\mathrm{r^*,t}} = \sum_s \mathbf{A}^{\mathrm{r^*s}} \mathbf{x}_{\mathrm{tp}}^{s,\mathrm{t}} + \sum_s \mathbf{f}^{\mathrm{r^*s,t}} \tag{3.35}$$

Where the first summation ($\sum_s \mathbf{A}^{\mathrm{r^*s}} \mathbf{x}_{\mathrm{tp}}^{s,\mathrm{t}}$) is the sum of vectors of dimension $nx1$, each of them accounting the intermediate inputs that region r^* supplies to other regions s. The second

[19] Note that here it is assumed that just the local demand is reduced, while imports for non-basic products remain the same. This assumption is following (Li et al., 2013).

summation ($\sum_s \mathbf{f}^{\mathrm{r}^*\mathrm{s,t}}$) is the sum of vectors of dimension $nx1$, each of them accounting the total final demand that each region s demands for final products from region r^*. Note that the intermediate demand in the MRIO table, $\mathbf{A}^{\mathbf{r}^*\mathbf{s}}\mathbf{x}^{\boldsymbol{s},\mathbf{t}}$, accounts for the intermediate inputs from region r^* that are needed for production in each other region s when $r^* \neq s$, and it represents the local intermediate demand when $s = r^*$. Likewise, final demand, $\mathbf{f}^{\mathbf{r}^*\mathbf{s},}$**,** considers the local final demand, when $s = r^*$, and the demand of other regions for products in region r^*, when $s \neq r^*$.

For each point in time, the vector of total demand for all regions includes this *new* final demand (household adapted demand and recovery demand) for the affected region ($\mathbf{x}_{\mathrm{td}}^{\mathrm{r}^*,\mathrm{t}}$). The vector of total demand for all sectors and all regions is of dimension $(n * q)x1$.

$$\mathbf{x}_{\mathbf{td}}^{\mathbf{t}} = \begin{bmatrix} \mathbf{x}_{\mathrm{td}}^{1,\mathrm{t}} \\ \mathbf{x}_{\mathrm{td}}^{2,\mathrm{t}} \\ \vdots \\ \mathbf{x}_{\mathrm{td}}^{\mathrm{r}^*,\mathrm{t}} \\ \vdots \\ \mathbf{x}_{\mathrm{td}}^{\mathrm{q},\mathrm{t}} \end{bmatrix} \tag{3.36}$$

Where each element $\mathbf{x}_{\mathbf{td}}^{\mathbf{r,t}}$ is a vector of dimension $nx1$ that accounts for the final demand of region r.

In the MRFF model, it is precisely this vector of total demand for all regions that is the source of changes in production in the other regions different from r^*. It accounts for changes in total demand in the affected region ($\mathbf{x}^{\mathbf{r}^*,\mathbf{t}}$) and, in consequence, the changes in intermediate production of all suppliers of region r^*, local and external. The new vector of production for all regions is:

$$\mathbf{x}^{\mathbf{t}} = \mathbf{A}\mathbf{x}_{\mathbf{td}}^{\mathbf{t}} + \sum_{s} \mathbf{f}^{\mathbf{s,t}} \tag{3.37}$$

Where each vector $\mathbf{f}^{\mathbf{s}}$ of dimension $(n * q)x1$ accounts the total final demand in region s of products from all other regions, including the local final demand in s:

$$\mathbf{f}^{\mathbf{s,t}} = \begin{bmatrix} f^{1s} \\ \vdots \\ f^{ss} \\ \vdots \\ f^{r^*s} \\ \vdots \\ f^{qs} \end{bmatrix}^{t} \quad (3.38)$$

Note that the vector of final demand influences the total demand only in the affected region r^*. Although this is an assumption that can be modified in the model. Nevertheless, to determine the distribution of the reduction in external consumption would imply more assumptions.

The total production of each region r at each period during the recovery is, then:

$$\mathbf{x}^{\mathbf{r,t}} = \sum_{s} \mathbf{A}^{\mathbf{rs,t}} \mathbf{x}_{\mathbf{td}}^{\mathbf{s,t}} + \sum_{s} \mathbf{f}^{\mathrm{rs,t}}$$
$$= \left[\mathbf{A}^{\mathbf{r1}}\mathbf{x}_{\mathbf{td}}^{\mathbf{1}} + \cdots + \mathbf{A}^{\mathbf{rs}}\mathbf{x}_{\mathbf{td}}^{\mathbf{s}} + \cdots + \mathbf{A}^{rr^*}\mathbf{x}_{\mathbf{td}}^{r^*} + \cdots + \mathbf{A}^{\mathbf{sq}}\mathbf{x}_{\mathbf{td}}^{\mathbf{q}}\right]^{t} \quad (3.39)$$
$$+ \left[\mathbf{f}^{\mathbf{r1}} + \cdots + \mathbf{f}^{\mathbf{rs}} + \cdots + \mathbf{f}^{\mathbf{rq}}\right]^{t}$$

Where each element of the summation ($\mathbf{A}^{\mathbf{rs}}\mathbf{x}_{\mathbf{td}}^{\mathbf{s}}$) is the $nx1$ vector of intermediate inputs that each region s needs from region r.

The indirect damage in each non-flooded region s, each time period, is determined by the difference in the production level accounting the effects in decreasing intermediate demand from the affected region and the pre-disaster level:

$$\mathbf{va}_{\mathbf{ind}}^{\mathbf{s,t}} = \mathbf{x}^{\mathbf{s,0}} - \mathbf{x}^{\mathbf{s,t}} = \mathbf{A}^{\mathbf{sr}^*}\mathbf{x}_{\mathbf{td}}^{\mathbf{r}^*\mathbf{,0}} - \mathbf{A}^{\mathbf{sr}^*}\mathbf{x}_{\mathbf{td}}^{\mathbf{r}^*\mathbf{,t}} \quad (3.40)$$

Finally, the total flood footprint ($\mathbf{ff}$) for all regions considers the direct damages in the affected region ($\mathbf{va}_{\mathbf{dir}}^{\mathbf{r}^*}$), the indirect damages in the affected region ($\mathbf{va}_{\mathbf{ind}}^{\mathbf{r}^*}$), and the in direct damages in the rest of the regions ($\sum_{\mathbf{s}\neq\mathbf{r}^*} \mathbf{va}_{\mathbf{ind}}^{\mathbf{s}}$):

$$\mathbf{ff}_{\mathbf{mr}} = \mathbf{va}_{\mathbf{dir}}^{\mathbf{r}^*} + \mathbf{va}_{\mathbf{ind}}^{\mathbf{r}^*} + \sum_{\mathbf{s}\neq\mathbf{r}^*} \mathbf{va}_{\mathbf{ind}}^{\mathbf{s}}$$
$$= \mathbf{f}_{\mathbf{rec}}^{\mathbf{r}^*\mathbf{,0}} + \left(\mathrm{T}^{\mathrm{r}^*}\left(\mathbf{x}^{\mathbf{r}^*\mathbf{,0}}\right) - \sum_{\mathrm{t}} \mathbf{x}_{\mathbf{tp}}^{\mathbf{r}^*\mathbf{,t}}\right) + \sum_{s\neq r^*} \left(\mathrm{T}^{\mathrm{s}}\left(\mathbf{x}^{\mathbf{s,0}}\right) - \sum_{\mathrm{t}} \mathbf{x}_{\mathbf{tp}}^{\mathbf{s,t}}\right) \quad (3.41)$$

This represents the final accounting framework developed under this thesis. The model in this stage is able to account for all direct and indirect economic effects occurred in the impacted region, the national region and the knock-on effects on economies in the rest of the world. Yet, there is room for further development. Some ideas are exposed in Chapter 8.

The next section describes the process for regionalisation, as the model is meant to be applied at a regional scale, and IO tables are not usually available at this scale. The technique used in this work is the Augmented Flegg Location Quotients (AFLQ).

3.6 Regionalisation of IO technical coefficients

As damages from natural disaster affect specific regions within a national context, and given that most available IO tables are available just at national level, it has been the case (for all case studies in this thesis) that the regionalisation of the IO has been necessary. This section describes the followed process to obtain the regional matrices for each case study.

Several techniques have been developed within the IO research field to *regionalise* the technical coefficients, where statistical techniques are the most widely used[20]. This thesis uses the Augmented Flegg Location Quotients (AFLQ) technique (Flegg & Webber, 2000; Miller & Blair, 2009; C. A. Romero, L. J. Mastronardi, & M. J. Faye, 2012) to obtain the correspondent regional IO coefficients matrices. This technique seeks to correct the national technical coefficients to depict regional technology, given the regional economic structure.

For this purpose, economic data on the *local* economy are used to re-scale the national coefficients, especially for employment, as this is one of the most reliable and available data sources at the sub-national level. The process consists of adjusting the national coefficients to the regional scale, by evaluating the relative size of each industry in the regional economy, in relation to the national size. Some parameters are also adjusted to consider the commercial traffic between the regional economy and other regions and the possible specialization of an industry within the region.

Then, the regional technical coefficient, r_{ij}, is derived from the national technical coefficients, a_{ij}, when re-sized by a regional-economy parameter or *location quotient*, lq_{ij}, such as in equation (3.42):

[20] It is argued that survey-based techniques are more accurate, although the main difficulty of these types of analysis is that they are highly consuming of time and resources. On the other hand, statistical techniques offer a quick and cheap alternative without losing much accuracy (A. C. Romero, L. J. Mastronardi, & M. J. Faye, 2012).

$$r_{ij} = lq_{ij} * a_{ij} \tag{3.42}$$

Where r_{ij} is the amount of input from industry i needed to produce one unit of output in industry j. Here we apply one of the most widely used location quotients, lq_{ij}, the AFLQ. The lq_{ij} represents the location quotient that is altering the national technical coefficient (a_{ij}), to represent the regional technology. For this work, the lq_{ij} term takes the values of the $AFLQ_{ij}$ described in this document.

We depart from the so-called simple location quotients (SLQ) to assess the relative importance of each regional industry i, as described in equation (3.43).

$$slq_i = \frac{re_i/tre}{ne_i/tne} \equiv \frac{re_i}{ne_i} * \frac{tne}{tre} \tag{3.43}$$

Where tre is total employment in the region, tne is total employment in the country, re_i is employment in the supplying region, and ne_i accounts for national employment in the same sector.

Then, the cross-industry LQ (CILQ) is derived from the SLQ to assess the relative importance of a supplier industry i regarding the purchasing industry j (see equation (3.44)):

$$cilq_{ij} = \frac{slq_i}{slq_j} \equiv \frac{re_i/ne_i}{re_j/ne_j} \tag{3.44}$$

Later, Flegg and Webber (1997) refined the regionalization in the Flegg LQ (FLQ) to correct for the persistent underestimation of regional imports in the CILQ through the parameter $\lambda = [\log_2(1 + tre/tne)]^{\delta}$ to obtain the FLQ. The parameter δ gives flexibility to the formula and its estimation is more related with the empirical analysis. The smaller is the value of δ, the bigger the value of λ, for any given $\left(\frac{tre}{tne}\right)$ ratio (Flegg & Webber, 2000).

Finally, in the AFLQ (equation (3.45)), one last parameter was added to cover the possibility of regional specialization in some sectors, $[\log_2(1 + slq_j)]$:

$$afl q_{ij} \equiv cil q_{ij} * \lambda * [\log_2(1 + sl q_j)] \quad (3.45)$$

This generated a quotient for each of the elements in the national matrix of technical coefficients, $\mathbf{A}$. Then, the regional matrix of technical quotients, $\mathbf{A}_{\text{reg}}$, is obtained when multiplying the national technical coefficients matrix ($\boldsymbol{A}$) by the correspondent location quotient ($\boldsymbol{AFLQ}$):

$$\mathbf{A}_{\text{reg}} = \mathbf{AFLQ} \,.\!*\, \mathbf{A} \quad (3.46)$$

So, for each national technical coefficient (a_{ij}) we obtain the regional counterpart (r_{ij}):

$$r_{ij} = afl q_{ij} * a_{ij} \quad (3.47)$$

3.7 Model limitations

It must be considered that the proposed methodology presents a series of limitations, as any modelling technique trying to capture certain phenomena of socioeconomic activity. Additional uncertainty arises from data. This section describes the main limitations to be considered under the flood footprint analysis.

3.7.1 Model rigidities

Regarding the model structure, the flood footprint model inherits some rigidities from the IO model -as previously mentioned in this chapter- that imply certain level of uncertainty. These are:

Price rigidities: It has been argued that facing inputs shortages during a catastrophe, prices would increase. This in turn would increase the external supply of goods (imports), reducing the scarcity. The same would apply to labour force: scarcity of labour would temporarily increase wages, and this would attract labour to the affected region. The final outcome is ambiguous, as on the one hand, costs increases with the prices increment. On the other hand, the 'injection' of goods and services from outside would speed the recovery, reducing the overall costs (Hallegate, 2008).

Leontief production functions: these functions implicitly assume there is no substitution between productive factors and inputs. If it is true the opposite extreme (perfect substitutes) is implausible as well, it has been proved a certain degree of substitutability between the productive factors. This would allow a production level higher than the minimum of any of the production inputs, implicating then lower costs for the replacement of productive inputs, or for higher production capacity.

Demand driven model: Even when the model considers shortages in productive factors, the model only captures the direct impacts in production due to supply disruptions. This is actually an improvement to the standard model which only captures changes in production caused by changes in final demand. However, the indirect impacts from supply disruptions are just captured as the reduction of intermediate demand. This has an underestimating effect in the model.

3.7.2 Model Parameters

Additionally, the development of the flood footprint comprises the introduction of some parameters that may introduce another degree of uncertainty. The uncertainty is especially high in those for which information is scarce. These are:

Disaster parameters/labour disruptions/population affected by travel delays: we take the parameter of travel delays from reports on the specific case study. However, we apply this evenly over all sectors. Information to clarify this is unavailable at the moment so that we have to apply a parsimony principle. The reduction of travel delay decreases over time during recovery. We model different trajectories, choosing usually a linear recovery as it does not represent significant reference with other trajectories, e.g. exponential, s-curve, etc.

Disaster parameters/labour disruptions/population unable to work by sector: There is no information on the distribution of affected people by sectors. Usually, damages information is on the number of people or households affected, but the information does not distinguish the industry sectors to which belong the affected employees. Therefore, the labour affected are distributed evenly among sectors.

Final demand parameter/recovery path: There is a lack of information on behavioural changes in final demand during a disaster's aftermath. We adopt a conservative change in final demand, equal to the minimum value in the EAV. A sensitivity analysis for each case showed that the model, at each stage, is not very sensitive to changes in this parameter, regardless the recovery path that is modelled. The same variation of parameters was applied to all case studies, which is a variation of ±30% with intervals of 5%. This leaded to an estimation of 13 different scenarios. It should be mentioned that we reported just the global sensitivity analysis, which comprises the variation of all parameters at a time. This is due to changes in final demand parameters provide non-significant variation in the results. The reported analysis shows the results vary less than proportionally than the changes in parameters, so that the results can be considered robust, regarding the uncertainty from the parameters.

IO tables/regionalization/economy size parameter: This is not part of the flood footprint model, however it regionalisation was needed in all case studies. The chosen technique for regionalisation incorporates a parameter that adjust for the 'size' and 'specialisation' of the regional economy which is calibrated with regional data. This parameter imposes uncertainty at industry level, as the adjustment is at aggregate level.

Rationing scheme/allocation rules: The rationing scheme used in the case studies for this thesis follow a prioritising-proportional allocations scheme. In allocating the remaining resources after a disaster, this means that intermediate demand is prioritised over final demand, and allocation among sectors and final demand categories follows the same proportional distribution as in the pre-disaster situation. We follow this assumption based on the sensitivity analysis carried out by Li et al (2013), who showed that other allocation strategies would delay the recovery, causing inconsistent results.

3.7.3 Information uncertainties

Disaster information/labour disruptions/people affected by flooding waters: there is no information on people affected in their homes or in their health and the industry where they work. Therefore, it is assumed a weighted distribution (in absolute terms) of labour affected by sector.

Disaster information/capital destruction/sectors allocation: information on damages to physical infrastructure is usually disaggregated in different categories as those of economic activity (industry sectors). The concordance between the two sets of information implies some assumptions to allocate capital damages to industry sectors. In the aggregate, it is the same cost so that for direct impact it does not bring high uncertainty. However, this may bring uncertainty in the indirect damages as these depend more on the interlinkages among industries.

Disaster information/capital destruction/damages: the standard estimation of costs from physical destruction (as in the damage functions) considers the average damage to a type of property given certain level of flood waters (or other disaster parameter). However, this is an external source of uncertainty that would affect estimates in any model.

Another limitation is related with the novel character of the research, as there are no other dedicated studies for appraisal of indirect damages for the selected case studies. This prevents the comparison of results with practical data. However, the model results are consistent with other researches. Those indicate that indirect damages keep a proportion with direct damages that ranges from 50% to 250%, depending on the magnitude of direct damages regarding the economy size (Hallegate, 2008; Li et al, 2013; Kocks, 2015; etc).

3.7.4 Model reliability

We have to accept the uncertainty arising from data, considering the mentioned limitations in this regard.

Respecting the uncertainties arising from model parameters, it was conducted a sensitivity analysis to test the reliability of the model and the robustness of the results. The results of sensitivity analysis are presented in the 'Results' section of each of case studies chapters.

The analysis shows that the model is stable, as changes in the parameters causes less than proportional changes in the results. The sensitivity analysis was carried out for each parameter, separately. However, here we present the global sensitivity analysis, as changes in single parameters would lead to non-significant changes in the results. With this, we can assure that the methodology presented in this thesis is relatively reliable (considering the inherent uncertainty from data and limitations from the standard IO model), and the results can be considered robust. Further refinement to the methodology to incorporate the increasingly refined data from other techniques/sciences would allow a more accurate estimation of damages and their dissemination along the value chain.

3.7.5 Model robustness

Regarding the robustness of the model related with underlying assumptions, this can be divided in two: assumptions inherited form the IO model, and assumptions from the recovery process.

Regarding the IO model, it has been argued that, in impact analysis, the related models tend to overestimate the costs, due to the assumptions which cause rigidities in production functions, prices, and inputs substitutions. On the other hand, it has been argued that models where these assumptions are relaxed, as in the GCE, the results are underestimated. However, it has been noted that in a disaster aftermath, some rigidities persist, although some of them would be overestimated. When it is possible to count with the estimations of both IO and CGE models for the same case, it is a consensual practice to consider the estimations of IO based model as the upper bound, while the results from the CGE based models would represent the lower bound (Cochrane, 2004; Okuyama, 2007, 2009; A. Z. Rose, 2004).

Regarding the assumptions about allocation of the remaining resources for recovery, Li et al (2013) carried out a sensitivity analysis on the related assumptions, i.e. what would happen if the priority scheme would be different.[21]

The analysis was for two cases: The first prioritises the final demand over intermediate and recovery demand. This situation shows a much slower recovery, compromising the functioning of the whole economy in the long run.

The second case uses a proportional allocation for intermediate, reconstruction and final demand. This case showed a similar recovery as with the rationing scheme applied in this thesis. However, it should be mentioned that the first case is not very plausible, as it has been documented it is a society's priority to attend the reconstruction needs after a disaster.

[21] For a deeper review on this, please refer to Li et al (2013).

Chapter 4 Flood Footprint of the 2007 Floods in the UK: The case of the Yorkshire and The Humber region

The outcomes of this chapter have been published in a paper co-authored by Dabo Guan, Zhao Zheng, Yang Xia and Anna Serrano. David Mendoza is responsible for modelling, results and conclusions. The sections in this chapter have been reproduced under the co-authors permission.

Mendoza-Tinoco, D., Guan, D., Zeng, Z., Xia, Y., Serrano, A. (2017) Flood footprint of the 2007 floods in the UK: The case of the Yorkshire and The Humber region, in Journal of Cleaner Production 168 pp. 655-667 https://doi.org/10.1016/j.jclepro.2017.09.016

The purpose of this chapter is to fulfil Objective 4, which is the empirical application of the first version of the flood footprint model (see Chapter 3.3. Standard Flood Footprint model). The main aim is to show the model outcomes for an empirical case, and to point out the lessons for the modelling improvements in the following stages.

At this stage, the analysis is conducted for a single region. The scale of the region depends on the political/economic demarcations within a country, as the availability of the economic data underlies to this.

The 2007 summer Floods in the UK was selected as the case study to achieve the purposes of this chapter. It was chosen based on its relevance, as it is one of the major flooding events in the last 100 years, which caused a major civil emergency nationwide. Thirteen people were killed and approximately 7,000 had to be rescued from flooded areas; 55,000 properties were flooded and over half a million people experienced shortages of water and electricity (Pitt, 2008). The region of analysis is Yorkshire & The Humber (Y&H), which was the most affected region during the event (see

Figure 4.1). The damages in the region accounted for 65.5% of total national direct damage. Approximately 1,800 homes were flooded, and more than 4,000 people were affected. Additionally, more than 64 businesses, schools and public buildings were flooded, and infrastructure services such as roads and electricity substations suffered significant disruptions as well (Ash, Fenn, Daly, & Wels, 2008).

Figure 4.1 Yorkshire and The Humber region within the UK

Source: Wikimedia Commons (2016)

4.1 Data gathering and codification

This section describes the data that is needed for the flood footprint model. All the data was collected, or regionalised when needed, for the region of Y&H, one of the 12 NUT2 regions of the UK. All values are for 2007, and when monetary they are in millions of pounds (£million) at 2009 prices. A monthly time scale is used for the temporal analysis, and the sectoral disaggregation uses 46 economic sectors. These sectors are disclosed in the EAV (Table 4.1).

The flood footprint model requires two sets of data: economic data about the affected region and information about the disaster.

4.1.1 Economic data

The economic data include information on capital stock, employment, and the IO tables. The economic information for employment, final consumption and output comes from the UK-Multisectoral Dynamic Model (MDM) by Cambridge Econometrics Ltd[22], a macro-econometric model used to analyse and forecast environmental, energy and economic data for the twelve NUTS2[23] regions in the UK.

[22] http://www.camecon.com/how/mdm-e3-model/

[23] According with the Eurostat organisation, 'The NUTS classification (Nomenclature of territorial units for statistics) is a hierarchical system for dividing up the economic territory of the EU for the purpose of: The collection, development and harmonisation of European regional statistics, socio-economic analyses of the regions, and framing of EU regional policies' (http://ec.europa.eu/eurostat/web/nuts/overview).

The regional matrix of technical coefficients, $\mathbf{A}$, was obtained from the UK matrix using the AFLQ described in the methodology section.

Capital stock data are only available at the national level from the official data of the national accounts[24]. The regionalisation consisted of obtaining the productivity of each sector at the national level and then adjusting by regional output, assuming the same productivity as the national average (Li et al., 2013). The regional dwelling capital is the proportion of housing in the region multiplied by the national dwelling capital. For the region of Y&H, this accounts for 8%.

4.1.2 Disaster Data

Ideally, the disaster data for the flood footprint model should comprise information of damages to industrial capital, residential capital, and infrastructure; reductions in labour capacity; and changes in final demand.

The information on damages to capital would conform the EAV, where the information can be collected in monetary terms or in relative terms to the total value of the affected capital. This information, in developed countries, is normally gathered by insurance companies. However, the information is rarely publicly available and secondary sources must be consulted to determine the damages to the industrial capital.

As the costs of flooding has traditionally focused on the physical damages, information about labour constraints and consumption behaviour after a disaster are more elusive than the former and most of the times must be inferred from other data sources. When there is no information, some assumptions are made for an exogenous modelling of labour damage and recovery.

For the case study analysed in this chapter, the main data source is provided by the UK Environmental Agency in the report 'Economic Impacts of Flood Risk on Yorkshire and Humber. Cost of 2007 Floods' (Ash et al., 2008).

For damages to industrial capital, the report states a total cost of £380 million for business premises, stock, equipment, etc. Additionally, the £470 million of damages to infrastructure are allocated to *infrastructure* sectors, namely Transport, IT services, Electricity & Gas, Water & Sewerage & Waste, PAD, and Education and Health sectors. As the sectoral disaggregation in

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[24] The data is available at https://www.ons.gov.uk/economy/nationalaccounts/uksectoraccounts/datasets/capitalstocksconsumptionoffixedcapital

the report is for 15 categories, an allocation of damage to each sector was made through a weighted distribution based on the relative weights of these sectors in the regional economy. These data were compared with original stocks of industrial capital to determine the proportion of affected productive capacity, i.e., the values of the EAV as presented in the Table 4.1.

Table 4.1 EAV for the 2007Floods in Y&H

Industrial sector	£million	% direct damage/capital stock		Industrial sector	£million	% direct damage/capital stock
Agriculture etc.	1.0	0.001%		Land transport	71.4	0.019%
Mining & quarrying	1.0	0.001%		Water transport	13.4	0.047%
Food, drink & tobacco	15.3	0.009%		Air transport	13.4	0.025%
Textiles etc.	14.6	0.026%		Warehousing & postal	7.3	0.001%
Wood & paper	15.0	0.089%		Accommodation	7.2	0.135%
Printing & recording	15.5	0.009%		Food & beverage services	7.3	0.014%
Coke & petroleum	15.2	0.031%		Media	7.5	0.007%
Chemicals, etc.	15.5	0.011%		IT services	94.4	0.231%
Pharmaceuticals	15.4	0.041%		Financial & insurance	24.1	0.012%
Non-metallic	14.6	0.009%		Real estate	24.4	0.031%
Metals	15.3	0.007%		Legal & accounting	0.5	0.033%
Computers, etc.	15.4	0.019%		Head offices & manag. co	0.1	0.038%
Electrical equipment	14.7	0.022%		Architectural & related	0.6	0.035%
Machinery, etc.	14.9	0.022%		Other professional services	2.7	0.032%
Motor vehicles, etc.	15.5	0.029%		Business support service	23.9	0.014%
Other trans. equipment	15.0	0.054%		PAD	41.4	0.009%
Other manuf. & repair	15.3	0.089%		Education	16.4	0.009%
Electricity & gas	91.4	0.014%		Health	39.4	0.064%
Water, sewerage & waste	101.4	0.109%		Residential & social	1.0	0.011%
Construction	7.0	0.014%		Arts	1.0	0.047%
Motor vehicles trade	7.6	0.012%		Recreational services	1.0	0.004%
Wholesale trade	7.3	0.182%		Other services	1.0	0.004%
Retail trade	6.9	0.095%		Unallocated	0.0	0.000%

Regarding residential damage, 10,759 houses were reported to be flooded, which represents 0.6% of total housing in the region. Total household damages were estimated at £340 million by the UK Environmental Agency.

Information on labour constraints is very scarce for this case, and the damaged labour was derived from the number of flooded houses multiplied by the average number of working people per household. Additionally, commuting delays were proportionally related to damage in the transport sectors. This results in a delay of 1 hour in commuting for 1.5% of the working population.

Finally, as information on changes in final demand is very scarce, we follow a sensitivity analysis over different levels of reduction in non-essential products and over diverse shapes of recovery curves. The values for the analysis show a decrease of 0.25% in households' demand for non-essential industries and a recovery time of 6 months with positive and marginally decreasing growth, i.e., a higher recovery rate for the first periods, which slows down at the end of the recovery.

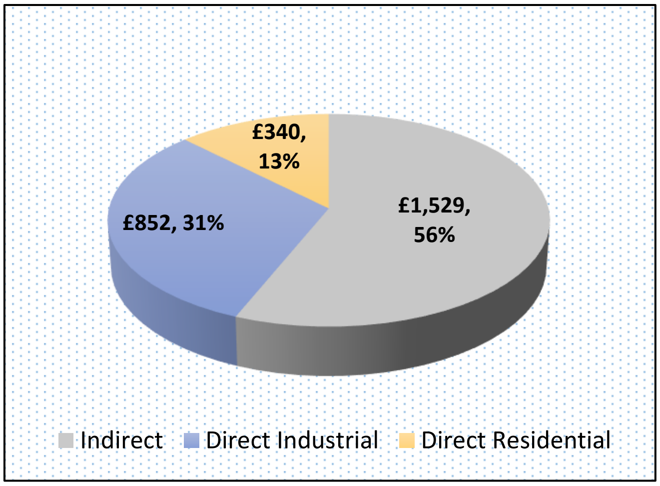
4.2 Results

4.2.1 Total Economic Loss for Yorkshire and The Humber region

For this case study it was used the standard flood footprint model. The first stage of the modelling development in the thesis. However, the model is fully capable to capture the direct and indirect economic damages caused in the impacted region without considering the effects in other regions directly or indirectly affected.

According to the flood footprint analysis, it takes at least 14 months for the economy of the Y&H region to return to its pre-disaster situation after the 2007 summer floods in the UK (Figure 4.2). This recovery includes both achieving economic equilibrium and returning to pre-disaster production levels. This entails a total economic loss of £2.7 billion, which is equivalent to 3.9% of the regional annual gross value added (GVA).

Figure 4.2 Flood Footprint. Damage composition (£million)



In differentiating direct economic loss from indirect economic loss, Figure 4.1 compares the shares of each category. The direct economic loss – including industrial and residential infrastructure damages – accounts for 1.7% of the yearly GVA (nearly £1.2 billion), of which the majority corresponds to industrial and infrastructural damages (71%). The indirect economic loss – including all non-realised product flow owing to productivity and demand shortages – accounts for an additional 2.2% of the city's GVA, at around £1.5 billion. This represents 56% of the total flood footprint.

4.2.2 Economic Recovery

The present section describes the progress of the economic variables involved in the recovery process.

Figure 4.3 Recovery process

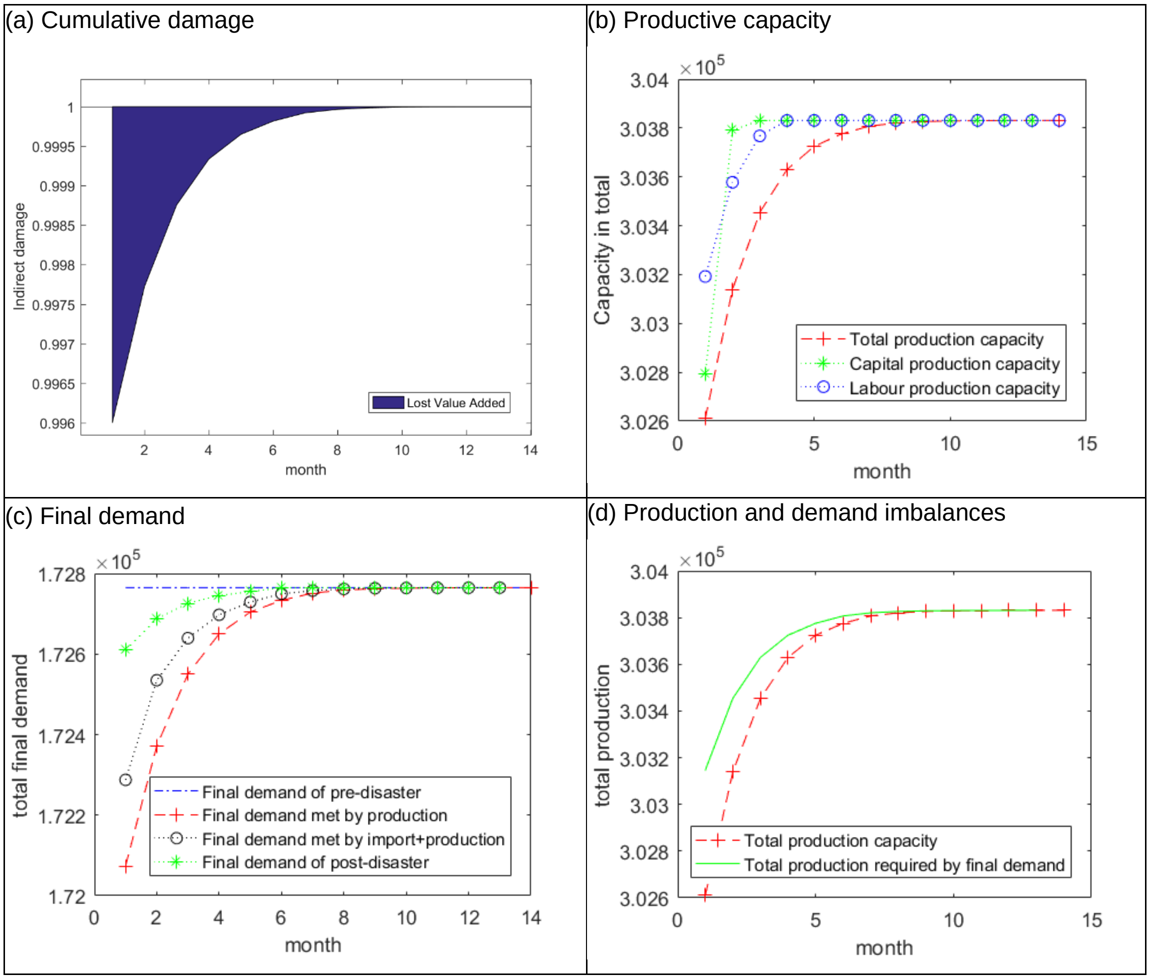


Figure 4.3. a) depicts the accounting of the cumulative damage during the recovery process. The area in purple, which indicates the distance between the final demand met by the available production at each time step and the pre-disaster level, represents the total indirect damage over the course of the recovery process. It can be noted that the initial shock represents a decrease of 0.4% of the productive capacity. The shape of the curve shows a fast recovery in the beginning, especially in the first 4-5 months, at which time the economy has recovered approximately 90% of its damaged productive capacity. It must be noted, however, that the recovery-curve shape is influenced by the rationing scheme chosen for the modelling, where the inter-industrial and recovery demand is prioritised over other final demand.

Figure 4.3 b) displays the recovery process of productive capacity, including both labour and industrial capital capacities. The figure indicates that industrial capital constraints constitute the main source of production disruptions in the first period after the disaster, being responsible for the 0.4% fall in productivity. However, this recovers rapidly, and labour disruptions happen to be the main constraint on productive capacity.

Figure 4.3. c) depicts the dynamics of final demand in the aftermath of the disaster. The green line indicates the adaptation and recovery process of the final demand. This variable includes the adapted behaviour of final consumers and the reconstruction demand. On the other hand, the red line shows how much of that adapted demand can be supplied by the actual constrained capacity of production. Part of the demand that cannot be satisfied by internal production is supplied through imports, as the black line illustrates.

Finally, Figure 4.3.d indicates the inequalities that remain between the level of production required by the final demand during the recovery process and the product supply from the surviving production capacity during the aftermath.

4.2.3 Sectoral Analysis

As the model is based on the IO model, one of the strengths of the flood footprint framework is its capability to provide an analysis at the industrial sector level. This is especially useful for disentangling the distribution of the knock-on effects as they propagate through the impacted economy and through other economic systems. Additionally, such capability of the flood footprint framework would provide convenience when planning for flood risk management and adaptation policies.

Figure 4.4 Sectoral distribution of damage

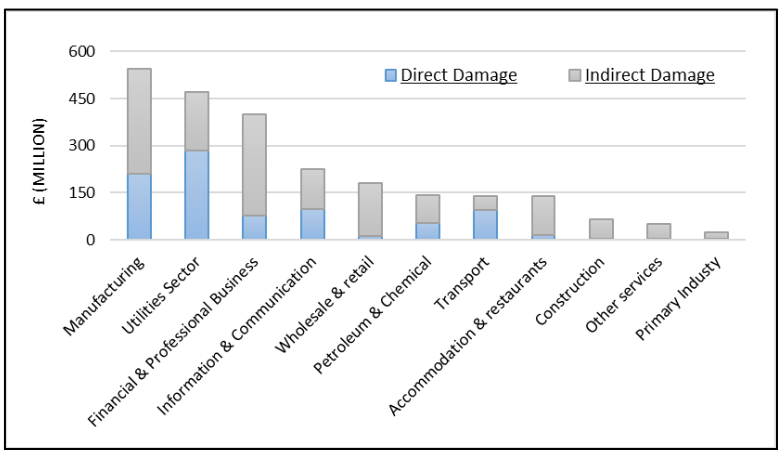
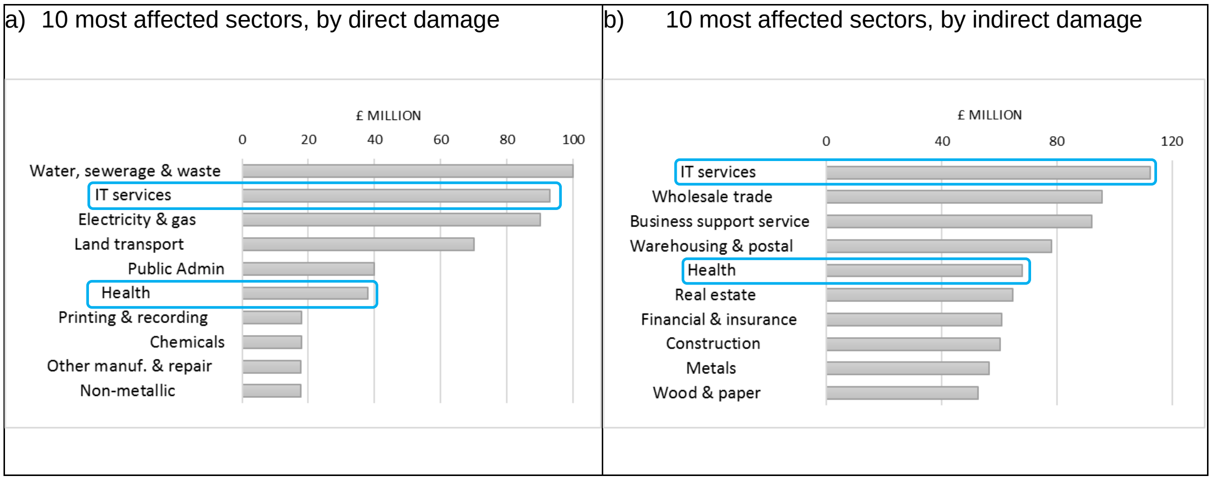


Figure 4.4 shows the distribution of the flood footprint for both direct and indirect damage among ten industrial groups. The proportions of direct and indirect loss present high

heterogeneity across the sector groups. For example, Manufacturing is shown to be the most affected sector, with a share of indirect loss 60% higher than direct loss, and the total damages in this group account for 23% of the total FF. The utilities sector suffers major direct damages (£190 million), as infrastructure damages are allocated among this sector. The Financial & Professional sector is the most indirectly affected, with 21% of total indirect damages, while just 9% of total direct damages are concentrated in this group.

Figure 4.5 The most affected sectors by different damage categories: Direct and Indirect damage



At a more disaggregated level (46 sectors), **Figure 4.5** depicts the ten most affected sectors for direct (a) and indirect (b) economic losses, respectively. The major direct damage is concentrated in those sectors forming the *Utilities Sector* group. The most affected sector is Water, Sewerage & Waste, accounting for 35% of direct economic loss in the Utilities Sector group and 12% of the total direct damage. Regarding indirect damages, the IT services sectors, from the Information & Communication group sector, was the most severely damaged, accounting for 86% of this group's losses and 11% of the total indirect damages.

Finally, it is noteworthy that two sectors appear in both categories: the IT Services and Health sectors. This indicates they are among the most vulnerable sectors in the region. The flood footprint in these sectors accounts for 13% of the total flood footprint.

4.3 Sensitivity analysis

Uncertainty in the model mainly comes from the lack of data in labour and final demand variables, and some assumptions applied to calibrate the correspondent parameters. To prove the robustness of the results, a sensitivity analysis is performed on labour and final demand parameters.

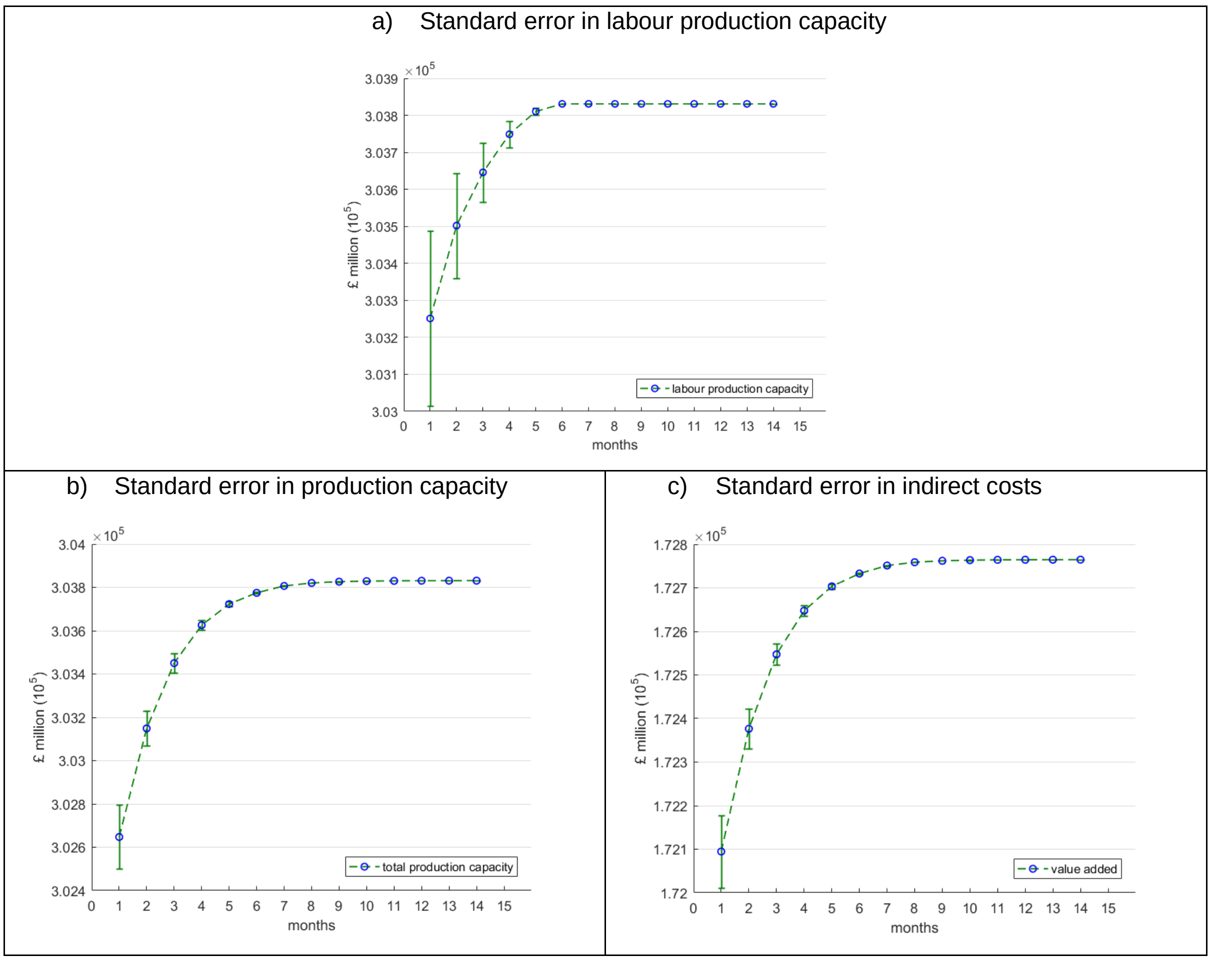
The sensitivity analysis comprises the upwards and downwards variation of 30% of the parameters in intervals of 5%.

4.3.1 Changes in labour parameters

The variation of parameters comprises the proportion of labour not available for traveling, and the proportion and time of labour delayed by transport constraints.

Figure **4.6**, shows that variations in labour parameters have a less-than-proportional effect in indirect costs and the total production capacity, and these are decreasing over time. Other variables are not affected by variations in labour parameters.

Figure 4.6 Sensitivity analysis for labour parameters



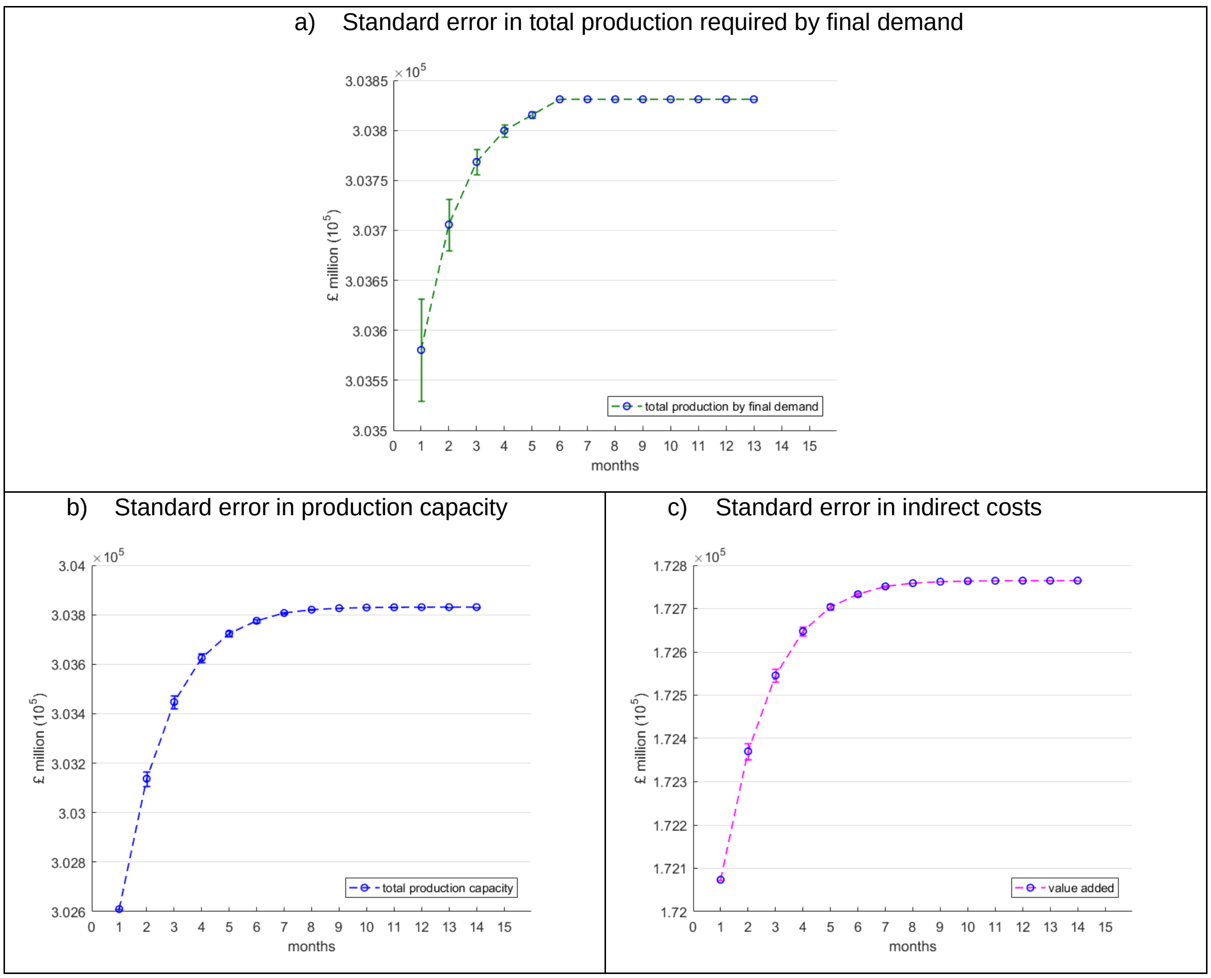
The standard deviation of the total variation of labour productive capacity is about £483 million, which causes a standard deviation of £297 million in total production capacity, and a standard deviation of $168 million in indirect damages.

4.3.2 Changes in final demand

The variation of parameters comprises the decreased proportion of consumption in non-basic products.

The results of the sensitivity analysis, as presented in Figure **4.7**, show that variations in final demand parameters have a less-than-proportional effect in indirect costs and the total production capacity, and these are decreasing over time. Other variables are not affected by variations in labour parameters.

Figure 4.7 Sensitivity analysis for final demand parameters



The standard deviation of the total variation of total production required by final demand is about £96 million, which causes a standard deviation of £93 million in total production capacity, and a standard deviation of $54 million in indirect damages.

4.4 Summary

The flood footprint model was successfully applied to assess the total economic loss resulting from a real past disaster event: the 2007 summer floods in the Yorkshire and The Humber region of the United Kingdom.

This constitutes the first study to apply the flood footprint framework to a real past disaster event. This analysis supports the important lesson that losses from a disaster are exacerbated by economic mechanisms that knock-on effects -or indirect damage- constitute a substantial proportion of total costs and that some of the most affected sectors can be those that are not directly damaged. For this case study, the proportion of indirect damages accounts for over half of the total flood footprint. Neglecting the impact of indirect damages would hide the real socioeconomic costs, especially in those sectors where direct damage is not very high.

There are, however, some caveats that must be noted. An impact assessment study is always subject to some degree of uncertainties. In this case, the data scarcity is the main source of uncertainty, making the use of strong assumptions unavoidable in certain parameters.

For the disaster data, the following case studies incorporate the use of the damage functions[25] and take advantage of the engineering flood modelling and GIS techniques that have recently evolved, providing more accurate sources of information.

Finally, although the model used in this case study effectively accounts for the knock-on effects in the affected regional economy, global economic interconnectedness requires us to move the analysis towards a multi-regional approach if we are to make an exhaustive impact assessment. This is the methodologically developed in sections 3.4 and 3.4 of Chapter 2.

[25]'Damage functions show the susceptibility of assets at risk to certain inundation characteristics, currently mostly against inundation depth' (Messner et al., 2007). This concept will be addressed in the next chapter.

Chapter 5 Single-regional modelling of multiple regions. 2009 Central Europe flooding and 2010 Xynthia windstorm

The purpose of this chapter is to fulfil Objective 4, which is the empirical application of the flood footprint model for multiple regions, for two different climate extreme events. The analysis of the case studies uses the model version in section 3.4, the Standard Flood Footprint model but for multiple regions. The used version of the model extends on the incorporation of the capital matrix, an element which adds methodological and conceptual consistency, as this element allows to translate the damages from a stock variable towards a flow variable. It also provides the distribution of sectors involved in capital restoration, and allows for recovery planning.

While Chapter 4 shows the effects of an extreme climatic event in a single region, this chapter extends the application of the flood footprint model to the appraisal of the economic damages on several regions. The effects of natural disasters are normally scattered among several political/economic regions, overpassing the national boundaries. Owing to this, a multiple-regions analysis along different countries is needed to fully capture the economic impacts of the hazard.

The other achievement of this chapter is the integration of the concept of the *capital matrix* to the analysis of the recovery process, providing consistent methodological and conceptual processes that describe how the investment in capital stock is transformed in new productive capacity.

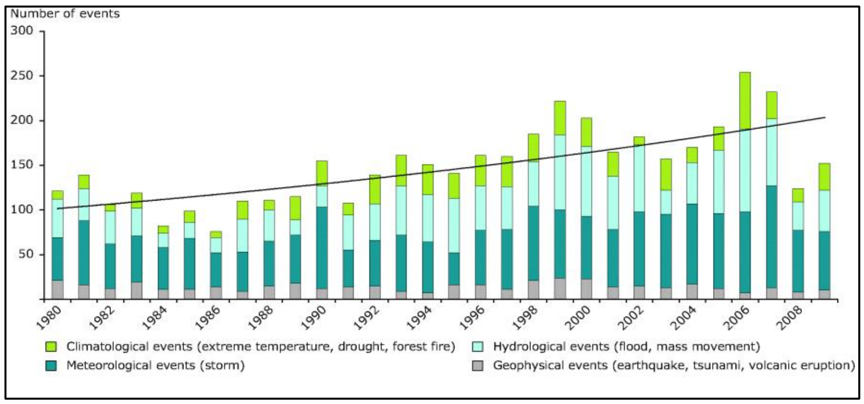
Additionally, this chapter demonstrates that the flood footprint model, originally developed for flooding events in mind, can be adapted to assess the economic impacts from a wide range of disasters. This should be possible whenever the physical damages caused by a disaster can be expressed in terms of a proportional damage to either of the productive factors, capital and labour. The use of damage functions in the flood footprint framework allows for this.

This chapter presents the impact assessment of two natural disasters affecting several sub-national regions in different countries within Europe. The first of them is the 2009 Flooding in Central Europe, and the second is the 2010 Windstorm Xynthia, which mainly affected Western and Southern Europe.

5.1 Exposure to natural disasters in Europe

In recent years, Europe has been increasingly affected by meteorological and hydrological events, with flood and windstorms being among the most frequent ones (see Figure 5.1). This urges for adaptation strategies *"[for] responding to current and future climate change impacts and vulnerabilities … within the context of ongoing and expected societal change"* (Isoard & Winograd, 2013).

Figure 5.1 Natural disasters in EEA member countries from 1980 to 2009



Source: EEA (2016)

Under these circumstances, the responsible institutions in Europe (e.g. the European Environment Agency (EEA)) must seek umbrella-type approaches to increase the adaptation and resilience of the affected regions.

The work of this chapter extends the impact analysis with the single-regional flood footprint model, to the assessment of several sub-national regions affected by the same hazard.

The method is applied to assess the *disaster footprint* of two different disasters affecting several regions in different countries in Europe. The first of them is the 2009 summer flooding in central Europe and the other one is the Windstorm Xynthia, affecting western and southern Europe in 2010. Additionally, the modelling incorporates the use of *damage functions*[26] and a *capital matrix* for the evaluation of different reconstruction pathways. These two new concepts, the damage functions and the capital matrix, represent an enhancement in the analytical framework, and they will be fully discussed later in this chapter.

[26] The damage functions are a tool to depict the vulnerability of exposed assets to the susceptibility of damage when in contact with hazard characteristics (Barredo, et al., 2008).

The structure of this chapter is as follows. Section 5.1.1 describes the data requirements. Section 5.2 provides a brief overview of each disaster, and presents the results of the analysis. Finally, section 5.3 provides a summary of the chapter.

5.1.1 Data

This section describes the needs and gathering of data to carry out the disaster footprint analysis of the selected cases.

The model requires information about the disaster damages, and information on the economic structure of each affected regions. For this case study, there are two differences in data gathering, compared with the previous case. The first is related to the use of damage functions to generate the values of the EAV's, while the second is the construction of the capital matrices.

The analysis for the 2009 Central Europe Flood uses information for 23 regions across Austria, Czech Republic, Germany and Poland. For the 2010 Windstorm Xynthia, the information comprises 82 regions within eight countries (France, Germany, Belgium, Spain, Italy, The Netherlands, The UK, and Luxemburg). The regional scale for the analysis is at NUTS2 level. All the information is disaggregated in the 14 industrial sectors in Table 5.1, and the monetary values are given in million euros at 2007 prices.

Table 5.1 Industrial sectors for analysis

Agriculture	Manufacture for recovery	Transport
Fishing	Utilities	Business services
Mining	Construction	Public sector
Manufacture food	Commerce	Other services
Manufacture general	Health and social	

5.1.2 Disaster damages

The disaster-data used for both cases were provided within the project Climate Extremes (Triple E Consulting, 2014) using the damage functions. The direct damages were in the EAV format for the flood footprint analysis presented in this chapter. The main source of information on the affected regions is the Natural Hazards Assessment Network (NATHAN)[27] of Munich Re and The Emergency Events Database (EM-DAT). This information was transformed into the

[27] https://www.munichre.com/en/reinsurance/business/non-life/nathan/index.html

EAV's using damage functions curves. The following is a description of how damage functions work.

5.1.3 Damage functions

In general, the damage functions translate the disaster parameters into economic damages in monetary terms.

These curves relate the characteristics of the hazard (e.g. water depth in the case of flooding); the exposure to the hazard, expressed as the affectations to physical assets (by land use or building type); and the vulnerability of the economy, as the maximum value of the damage for the affected assets (by industry category). This provides the distribution of the value of the damages by industry.

There are several methods to construct the damage functions. Those used in the analysis of this chapter follow the synthetic method, which consists of determining the average value of damage for each building-type according with the land use category, at each level of the hazard characteristics, e.g. the monetary value of the damage of a residential building given certain level of water during a flooding event. The process is to determine a maximum level of damage related to the maximum level of expected water depth. Then, each level of water depth (according with the probability distribution of occurrence) is related to a percentage of the maximum damage value. This provides with a probability function that assigns a monetary value, for each asset-type, to the probability of occurrence of each disaster event (normally expressed as the return-period in years) (Penning-Rowsell et al., 2013).

For the analysis of the flooding event, the values of direct damages where obtained through the widely-used standard-method (HIS-SSM), which combines the synthetic damage functions, with the use of flood maps, and land use maps (Moel & Aerts, 2011; Triple E Consulting, 2014). The flood maps provide the distribution of floodwaters in the affected region that is specific for the return period event. The land use and building-type maps relate each building-type to a land use category. When combining with the flood maps, this assigns a flood level to each building-type, which in turn is related to a land use category. Then, the damage function assigns a monetary value of the damage caused by a specific level of water in a specific building-type related to a specific land use category.

Finally, the information on building-type and land use category allow for the allocation of damages by industry category. A concordance matrix was developed with the purpose of assigning land use categories to the correspondent industrial sectors.

The values of the EAV containing the share of damage to the industrial capital are determined for each region.

The process for the construction of the Windstorm EAV followed the same methodology. Here, the parameters considered in the construction of the damage functions include the velocity of the winds and flood water depth.

5.1.4 IO tables

The regional IO tables for this analysis use the information from the RAEM-Europe model, a regional-economic model for EU27 (Ivannova, Bulasvskaya, Tavasszy, & Meijeren, 2011). The raw data emanate from Eurostat's[28] statistics. Later, the RAEM model regionalises them at NUTS2 level, and aggregate the information in 14 different industry categories. The variables from the RAEM consider, among others, output, labour, capital stock, intermediate consumption, final consumption, and imports.

5.1.5 Capital matrix

This section explains the process to construct the capital matrices that were used for the analysis in this chapter. The capital matrices used for the analysis in this chapter follows the process described in (Triple E Consulting, 2014), using the latest update in 2016.

The capital matrix contains the information about how much of capital stock, as a productive factor, is needed for the production in each industry; and which sectors are involved in the construction of this capital. In the case where a disaster destroys part of the capital stock, the capital matrix provides the 'recipe' to rebuild the capital stock and, consequently, productive capacity.

The capital stock data used to construct the capital matrices was taken from the EU KLEMS database, which is publicly available at http://www.euklems.net (The Conference Broad, 2016). The data used are from the file 'Real fixed capital stock (2010 prices)' and is available at

[28] http://ec.europa.eu/eurostat

national level. Where the data was not available for a country, the data from another country was used as a proxy, as in Table 5.2.

Table 5.2 Availability on capital data for affected countries

Countries	Availability of capital data (Yes/No)	Country used as proxy
Austria	Yes	-
Belgium	No	Netherlands
Czech Republic	Yes	-
Germany	Yes	-
Spain	Yes	-
France	No	Germany
Italy	Yes	-
Lithuania	No	Czech Republic
Luxembourg	No	Germany
Latvia	No	Czech Republic
Netherlands	Yes	-
Poland	No	Germany
Portugal	No	Spain
United Kingdom	Yes	-

The capital stock data is disaggregated to show how the capital stock of each sector is built up, i.e. the capital stock of sector i is the sum of the capital products from those sectors involved in capital formation, $\sum j^*$, where the * correspond to those sectors in the EU KLEMS database (Table 5.3).

Table 5.3 Sectors involved in capital formation

Code in EU KLEMS database	**Description**
K_IT	Computing equipment
K_CT	Communications equipment
K_Soft	Software
K_TraEq	Transport Equipment
K_OMach	Other Machinery and Equipment
K_OCon	Total Non-residential investment
K_RStruc	Residential structures
K_Other	Other assets

A concordance matrix was also used to match the sector disaggregation from the EU KLMS data with the 14 sectors disaggregation used in this chapter.

To maintain data coherence, the totals of the capital matrices were rescaled to match the capital stock data in the NEG dataset. So that in the aggregate, the relation capital/product in the NEG database remains.

Finally, to obtain a set of coefficients matrices, $\mathbf{K}^{\mathrm{r}}$, each element of the $j\mathrm{th}$ column was divided by the output of the $j\mathrm{th}$ industry to show the proportions of products required to build the capital stock that increases the productivity of sector $j\mathrm{th}$ by one unit. One matrix for each country was built, and used as the average capital productivity for all the regions within that country.

5.1.6 Labour damage

As data on labour constrains in the aftermath of a disaster is scarce or non-existent, proxy variables were used to develop an exogenous labour damage curve. For this purpose, the proxy used was damage to the transport sector and affected households. The labour constraints were defined as 1 in 10,000 employees unable of attending work, and 1% of the working population delayed by half an hour on average during the first month. Labour is fully available by the third month. A sensitivity analysis was carried out to test robustness in the parameters.

5.2 Results

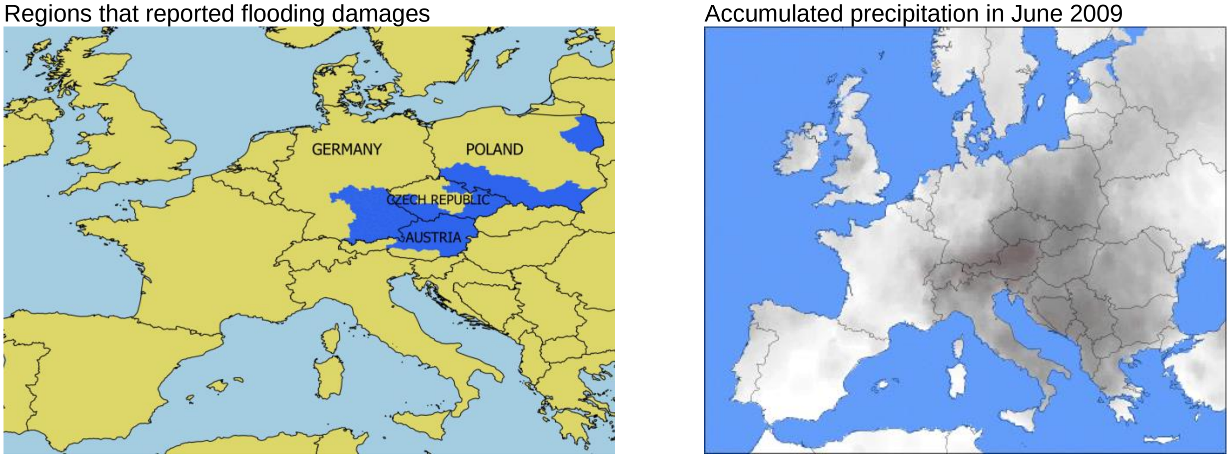
This section briefly introduces each of the case studies, and presents the results of the modelling for the cumulative direct and indirect effects, in each case.

5.2.1 2009 Central European Flood

The 2009 Summer Flooding in Central Europe was caused by an intense rainfall in late June 2009, which caused floods across several countries in Central Europe. The worst affected were Austria, the Czech Republic, Germany and Poland. The left map of Figure 5.2 shows the 23 regions at NUTS2 level with the most considerable flooding damages. They were considered for the analysis. Other countries that experienced heavy rainfalls and flooding alerts were Romania, Slovakia and Hungary, but with no significant damages reported. Most of the damages were caused by the overflow of some banks of the river Danube, and some tributaries, such as the Isar and Lech rivers. The disaster was responsible for 13 casualties, 12 in the Czech Republic and one more in Poland. The event also represented the worst Austrian floods in more than a century.

Figure 5.2 Regions under influence of heavy rain and river overflows during 2009 summer floods

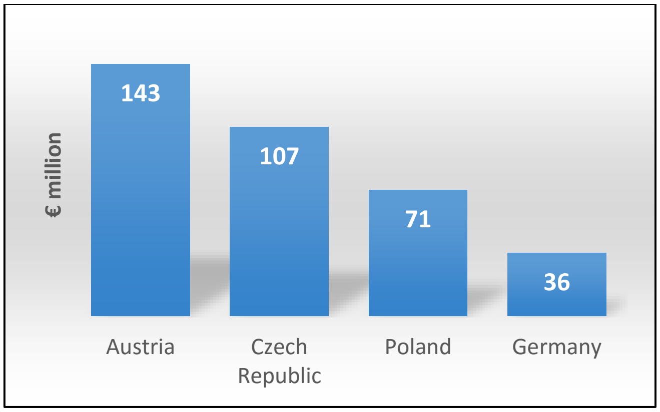
Regions that reported flooding damages | Accumulated precipitation in June 2009



Source: own elaboration with information from the GADM database (www.gadm.org). | **Source:** Commons Wikimedia (2017. a)

The flood caused material damages mainly to businesses, residential properties, roads, railways, power stations, the water industry, and field crops. The total damage was estimated to be €356 million distributed across countries as shown in the Figure 5.3:

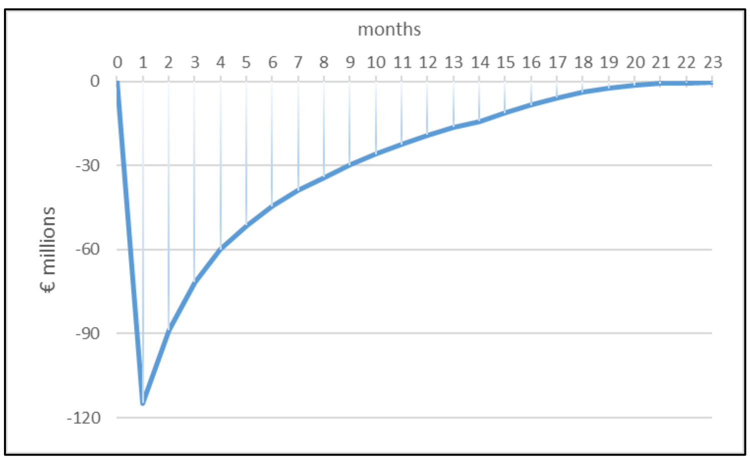
Figure 5.3 Value of material damages by country



5.2.1.1 Flood footprint results

The flood footprint model estimates that 23 months were needed for full recovery in all affected regions, although some regions would recover faster. Figure 5.4 shows a rapid recovery in the first 5 months; then an almost linear tendency until the 20th month, with three further months allowing for equilibrium adjustments.

Figure 5.4 Economic recovery path for 2009 flood case study

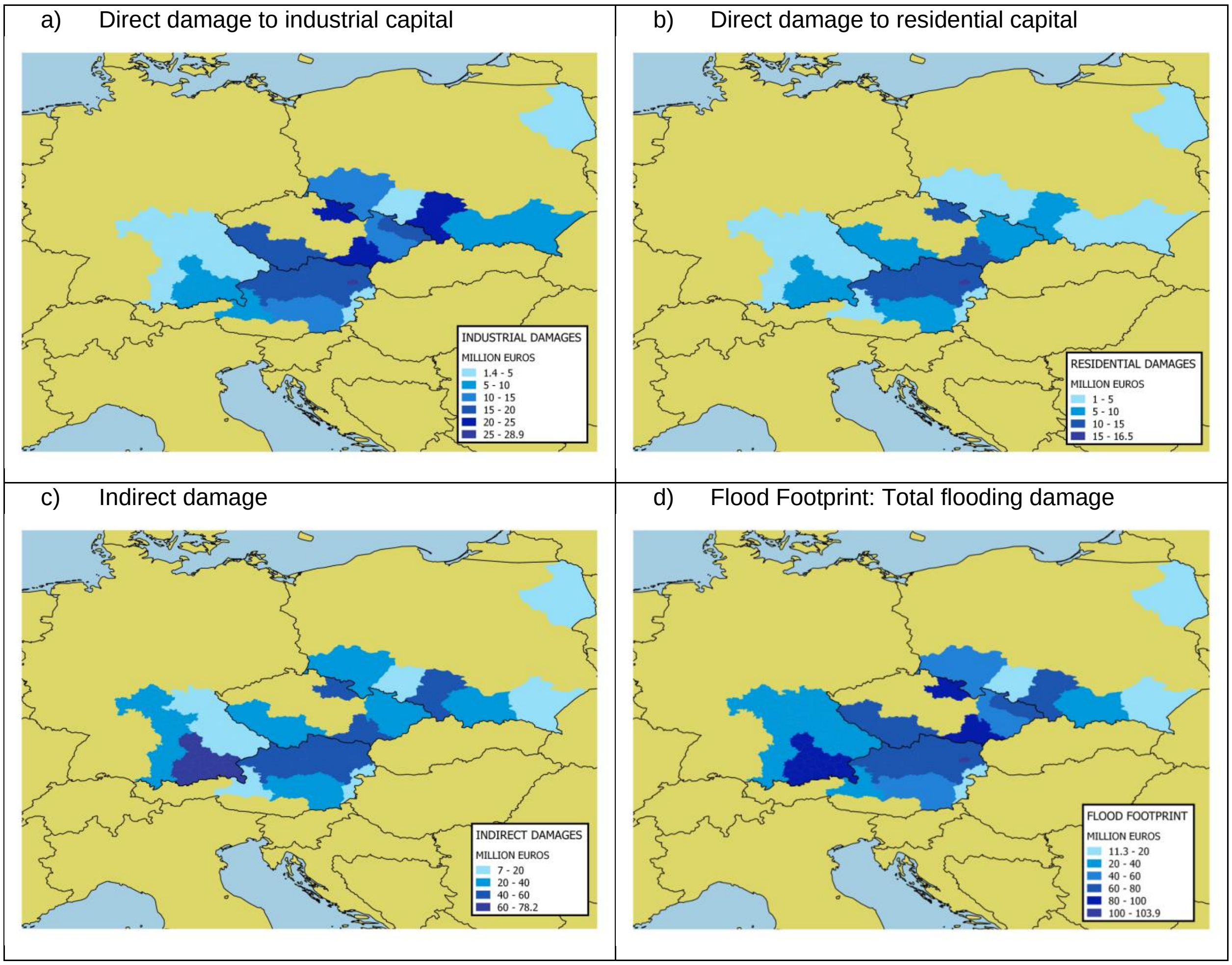


5.2.1.2 Direct and indirect impacts of the 2009 flood event

The initial direct damage to industrial capital in the four central European countries totalled at €238 million, which is equivalent to 0.004% of total capital stock among the affected regions. In addition, direct damages to residential capital totalled at €118 million, across all affected regions.

On the other hand, the indirect damages accumulated during the 23 months of the recovery that adds a total of € 663 million to the flood footprint of the disaster event. Therefore, the final flood footprint for the 2009 flooding in central Europe amount at over €1 billion. This is equivalent with the 0.04% of German annual GDP in 2009. The maps in Figure 5.5 show the regional distribution of each category of damages among the 23 affected regions across Austria, Czech Republic, Germany and Poland.

Figure 5.5 Regional distribution of damages of the 2009 flooding in Central Europe



5.2.1.3 Direct industrial damage

The upper-left map Figure 5.5 (a) depicts the distribution of direct damages to industrial capital. Austria was the most affected country with 38% of all damages of this category (ca. €91 million). Within Austria, Vienna (the darkest region) was the most affected region accounting for 32% of direct industrial damage. The distribution of damage to the industrial capital of the other countries include the Czech Republic with 31%, Poland with 23% and Germany with 8%. Two other notable affected regions are Jihovýchod in south-eastern Czech Republic (€22 million) and Śląskie in southern Poland (€20 million).

5.2.1.4 Direct residential damage

The upper-right map Figure 5.5 (b) shows the distribution of direct damages to residential capital. Again, Austria was the most affected country with 44% of the total damage in this category (ca. €52million). The three most affected regions are localised within Austria: Vienna (the darkest region) with 32%, Niederösterreich (Lower Austria) with 21% and Oberösterreich (Upper Austria) with 20% of the national residential damage. Other seriously affected regions outside Austria are Jihovýchod in the Czech Republic (ca. €10million), Oberbayern (Upper Bavaria) in Germany (ca. €7million) and Slaskie in Poland (ca. €6.5million). It is notable that damages in Oberbayern represent 40% residential damage in Germany; while damages in Slaskie represent 38% of residential damage in Poland.

5.2.1.5 Indirect damage

The indirect damages caused by constraints in labour and industry, in Figure 5.5 (c), constitute two thirds of the total flood footprint. The most severely affected country is Austria, with 31% of total indirect damages (€204million), while the most terribly affected region is Oberbayern in Germany accounting for 36% (€63million) of national indirect damages. Other notable regions include Vienna, Austria, whose damages represent 29% (€58million) of the national indirect damages, as well as Jihovýchod in the Czech Republic (€49million), and Slaskie in Poland (€43million).

5.2.1.6 Flood footprint

The total economic damage of the disaster is added up in accordance with the flood footprint concept. This includes all incurred costs by direct and indirect damages. The geographical distribution of the flood footprint is presented in the lower-right map Figure 5.5 (d). This shows that Austria experienced the largest proportion of damages, accounting for over one third of the total flood footprint (€347million). The Czech Republic contributes over one quarter (€268million), while Germany and Poland contribute with 20% (€211million) and 19% (€193million) respectively. For comparative purposes with their respective national GDP, the flood footprint in Austria represents 0.12%, in the Czech Republic the 0.15%, in Germany the 0.015%, and in Poland the 0.03%.

5.2.1.7 Sectoral distribution

This section presents the distribution by economic sector of both direct and indirect damages for all affected regions. It must be noted that direct damages to residential capital are excluded from these figures, as they do not affect the productivity of industrial capital.

Figure 5.6 Distribution of direct and indirect damage by economic sector

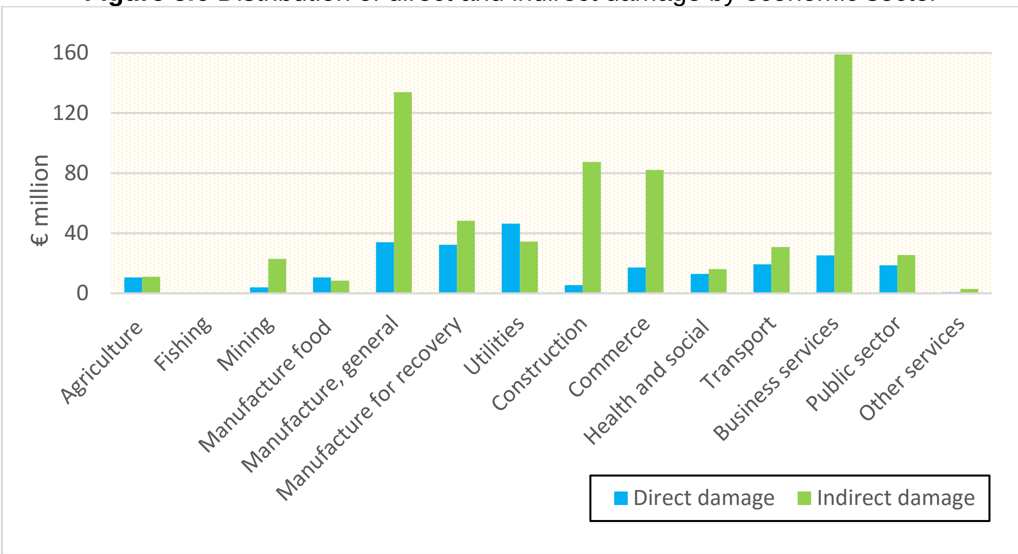


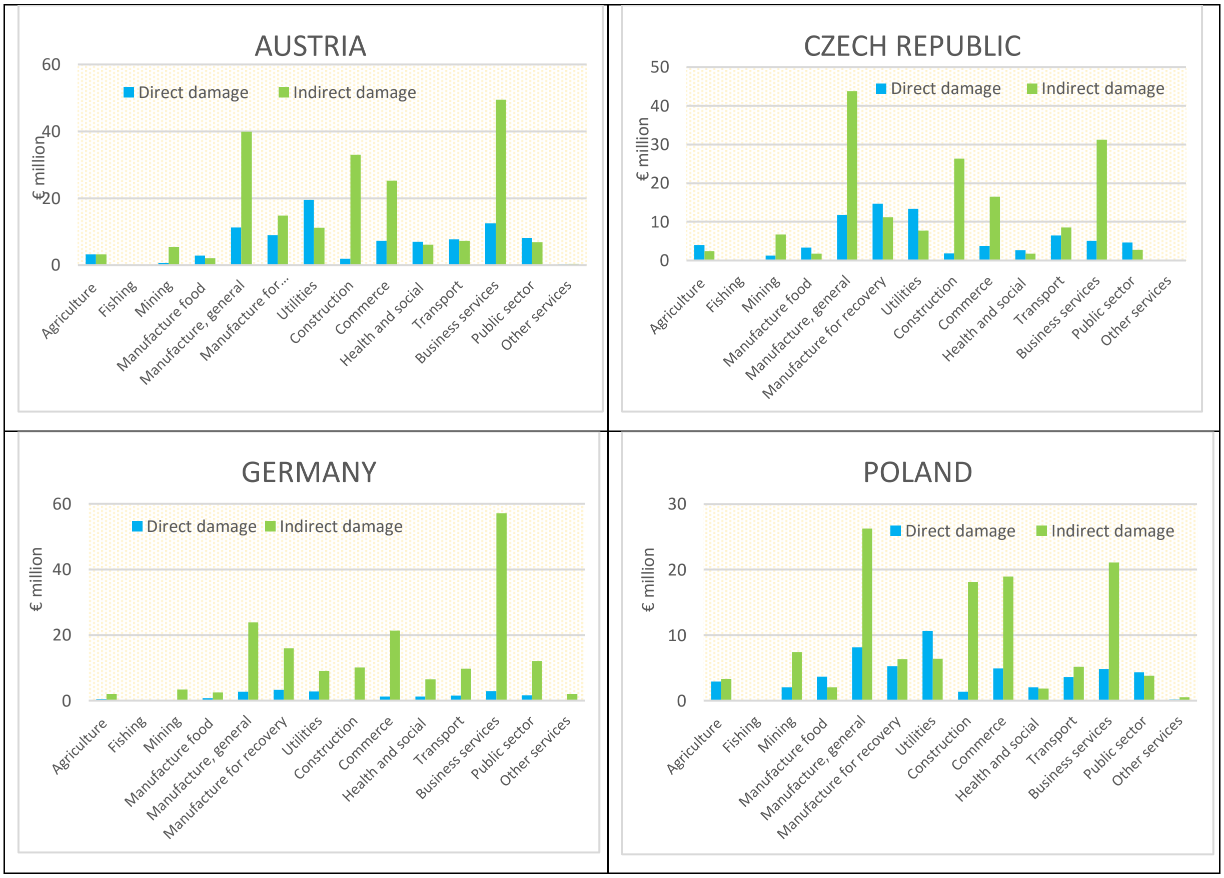
Figure 5.6 depicts direct and indirect damage across each of the 14 industrial categories. The most affected sectors by direct damages are Utilities; Manufacture general; and Manufacture for recovery sectors. These three sectors account for 47% of total direct damage (€112.5million). On the other hand, the indirect damages accrue in Business services, which is the most affected sector accounting for around one quarter of total indirect damages (€159million); followed by Manufacture general (€134million); Construction (€87.5 million); and Commerce (€82 million) sectors. These four sectors account for 70% of the total indirect damage.

5.2.1.8 Sectoral distribution by country

Figure 5.7 National distribution of direct and indirect damage by industrial sector

shows the distribution by economic sector of direct and indirect damage for each affected country.

Figure 5.7 National distribution of direct and indirect damage by industrial sector



In Austria, direct damages account for €91 million, while indirect damages account for €205 million. Around half of direct damages are concentrated in Utilities (€19.5 million), Business services (€12.5 million), and Manufacture general (€11.3 million) sectors. On the other hand, 60% of indirect damages are concentrated in Business services (€49.5 million), Manufacture general (€40 million), and Construction (€33 million) sectors.

In the Czech Republic, direct damages account for €73 million and indirect damages account for €160 million. Manufacture for recovery (€14.7 million), Utilities (€13.4 million) and Manufacture general (€11.8 million) concentrate 54% of direct damages. Regarding indirect damages, 47% are concentrated in Manufacture general (€43.8 million) and Business services (€31.2 million) sectors.

Direct damages in Germany account for €19 million and indirect damages for €175 million. Manufacture for recovery (€3.3 million), Business services (€3 million) and Utilities (€2.8 million) sectors concentrate 47% of direct damages. On the other hand, Business services sector on its own concentrates one third of indirect damages (€57 million).

In Poland, the direct damages represent €54 million, and the indirect damages account for €121 million. The sectors in Poland most affected by direct damage are the Utilities (€10.6 million), and Manufacture general (€8.1 million), which together represent 35% of the total. Around 70% of indirect damages are accumulated in Manufacture general (€26 million), Business services (€21 million), Commerce (€19 million), and Construction (€18 million) sectors.

5.2.1.9 Sensitivity Analysis. 2009 floods in Central Europe

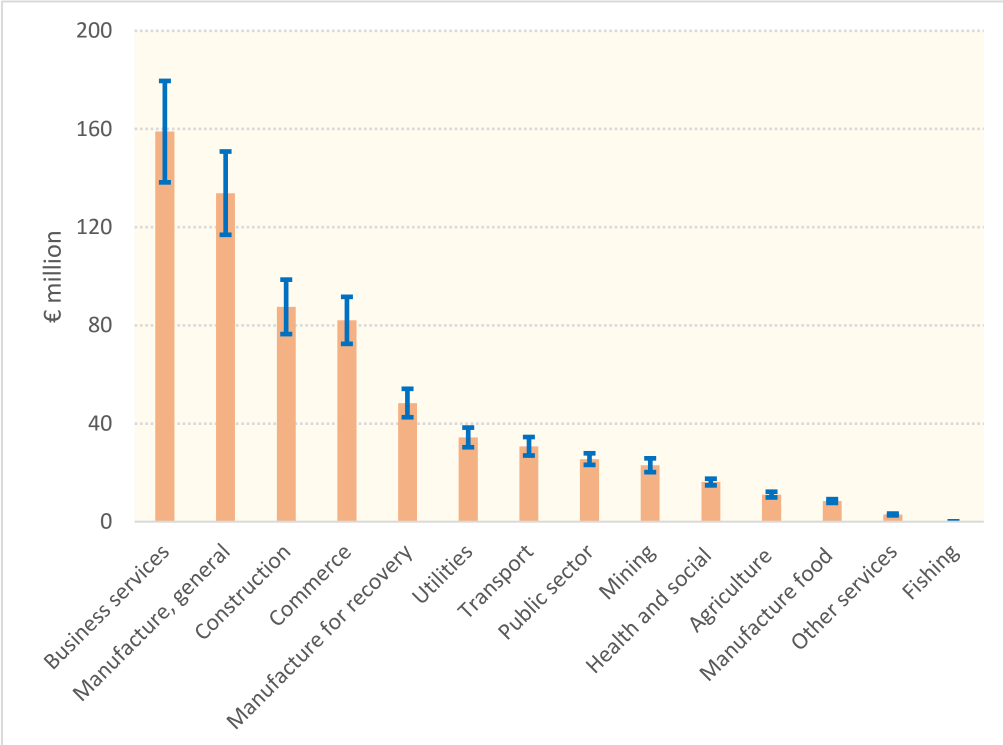
A sensitivity analysis was carried out on the model parameters related with the damage curve for labour, and behavioural changes in final demand.

The sensitivity analysis comprises the upwards and downwards variation of 30% of the parameters in intervals of 5%.

Related to final demand, the variation of parameters comprises the decreased proportion of consumption in non-basic products. While for labour, the variation of parameters comprises the proportion of labour not available for traveling, and the proportion and time of labour delayed by transport constraints. Here are presented the results of a global sensitivity analysis, this is, the results of variations in all parameters at the time. This is due to changes in final demand parameters gave non-significant changes in results.

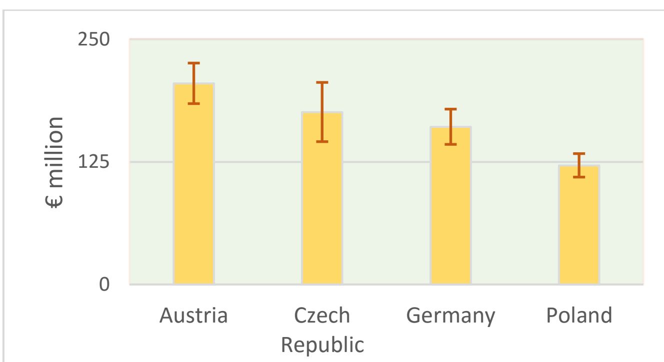
The error bars in Figure 5.8 show the standard error by industry sector, from the sensitivity analysis. In average, the standard error is 11% different from the mean values. The maximum error, in relative terms, is found in the Business Services sector, which represent a deviation of 13% regarding the mean values. The maximum error, in absolute terms, is found in the Manufacture General sector, which represent a deviation of €17 million. The standard error of the overall result (the variation in total indirect damage for all sectors in all regions) is 12% different from the mean (± €662 million).

Figure 5.8 Sensitivity analysis, by sector



In Figure 5.9, the error bars represent the variation given by the standard error from the sensitivity analysis, by country. It can be noted that the distribution of the error is more heterogeneous than by sector. This is mainly due to the variation is distributed among less categories. The maximum error, in relative terms, is found in the Germany, which represent a deviation of 17% regarding the mean values. The maximum error, in absolute terms, is found in Germany as well, which represent a deviation of €30 million (37% of total standard error).

Figure 5.9 Sensitivity analysis by country



The sensitivity analysis shows that the model is relatively stable, and the results can be considered robust, as variations in the model parameters causes less than proportional changes in results. In this case, a variation of ± 30% in the parameters values results in a standard error equivalent to 12% of the mean value of the total indirect damages of the event.

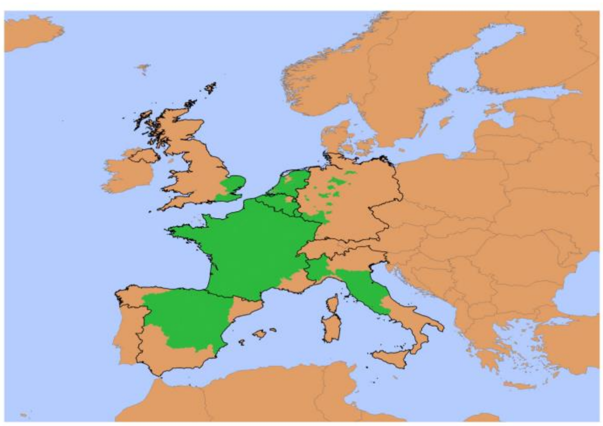
5.2.2 2010 Windstorm Xynthia

In late February 2010, the powerful storm Xynthia, from the Atlantic Ocean, crossed Southern and Western Europe with strong winds up to 175 kmph, causing a rise in sea levels, and heavy rainfall. It was the costliest natural disaster of 2010, which together with Windstorm Klaus (in the same year) resulted in 65 casualties and £4 billion in material damages (Triple E Consulting, 2014).

Figure 5.10 shows the area affected by the storm, as well as the direction and intensity of winds in the different regions of Western and Southern Europe. The left side of the map show the 82 NUTS2 regions considered for the analysis of this case study.

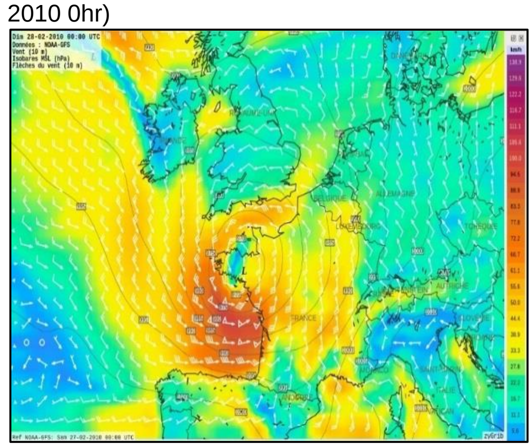
Figure 5.10 Regions under influence of the 2010 Xynthia Windstorm

Regions that reported windstorm damages



Source: own elaboration with information from the GADM database (www.gadm.org).

Visualisation of the storm Xynthia (28 February 2010 0hr)

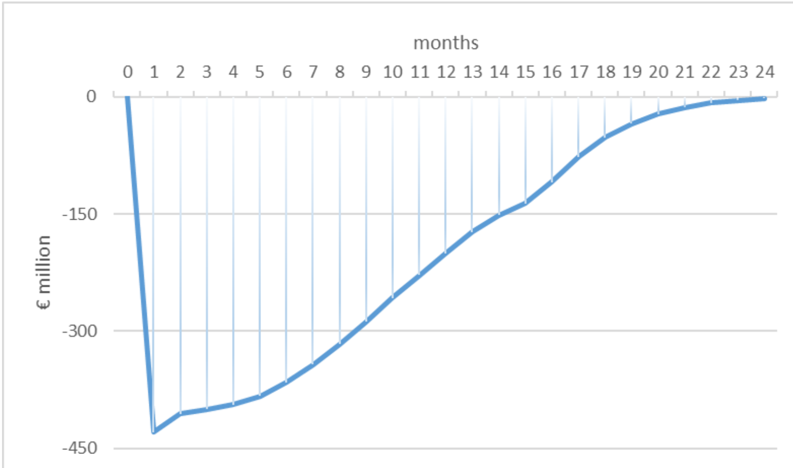


Source: Commons Wikimedia (2017. b)

France was the worst affected country, with Belgium, Germany, Italy, Luxemburg, Spain, The Netherlands, and the United Kingdom also reporting casualties and material damages. The transport sectors were severely affected across the countries, including roads, railways and flights. Power stations and electric networks were badly damaged, leaving up to one million households without electricity for up to three days across the impacted regions, but especially in France.

For this event, the model estimates the total recovery period required as 24 months, with a nearly linear recovery pattern for the first 18 months, and a slowing pace of recovery in the final six months (Figure 5.11). It should be noted that, as in the previous case, some regions might achieve recovery in less than 24 months, partially explaining the shape of the recovery curve for the last s months.

Figure 5.11 Economic recovery path for 2010 Windstorm Xynthia case study

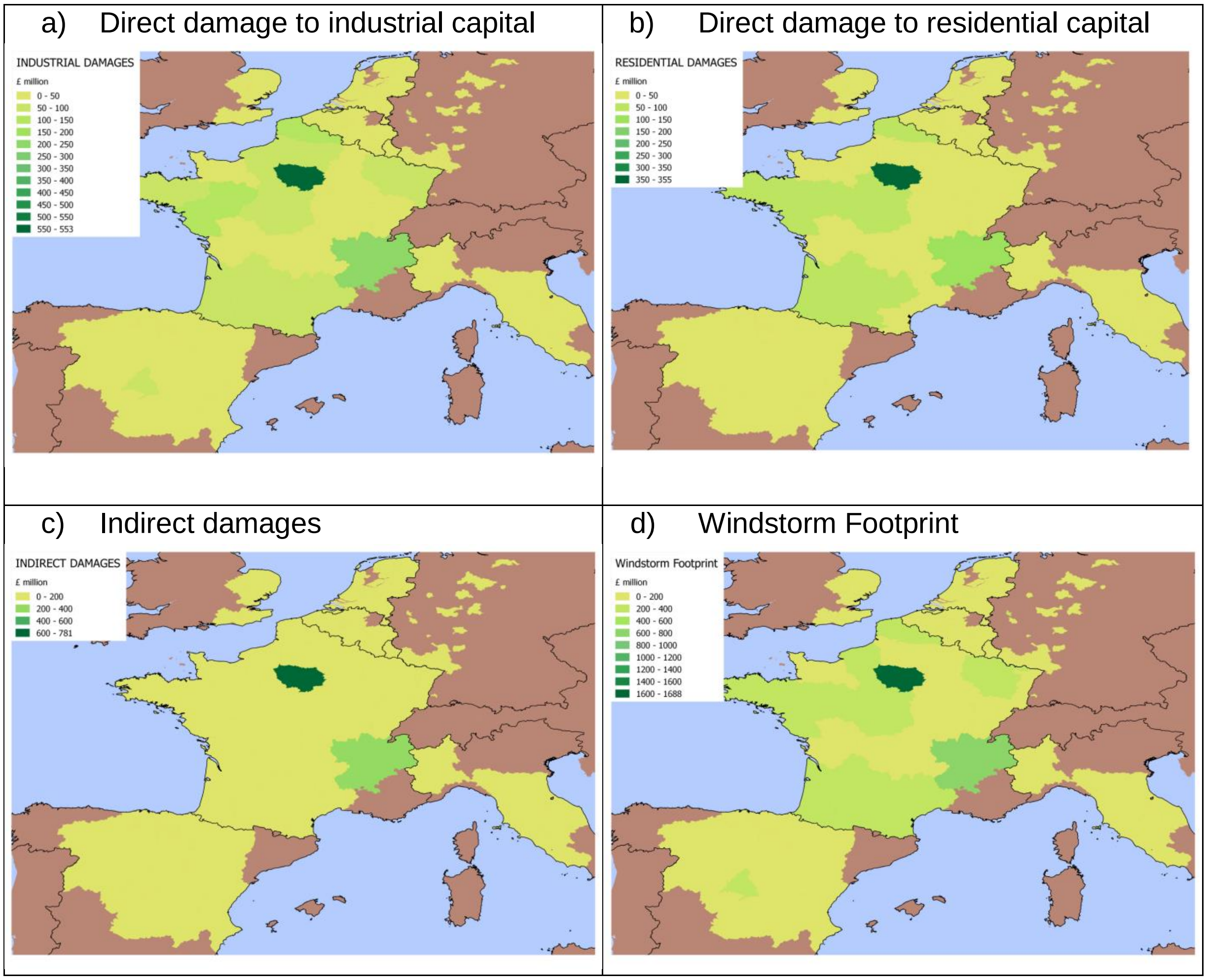


5.2.2.1 Direct and cumulative indirect impacts of 2010 windstorm event

The direct damage to industrial capital in the eight affected countries totalled € 2.5 billion. This amount is equivalent to 0.007% of the total capital stock of all affected regions. The direct damages to residential capital add other €1.7 billion to these direct damages. This represents a total direct damage of €4.2 billion.

Additionally, the cumulative indirect damages totalled € 4.8 billion during the first 24 months of recovery. Therefore, the flood footprint for the 2010 Xynthia windstorm event amounts to over €9 billion. This is equivalent to 0.35% of German annual GDP in 2010. The maps in Figure 5.12 show the regional distribution of each category of damages among the 82 affected regions within Belgium, Germany, Spain, France, Italy, Luxemburg, The Netherlands, and the UK.

Figure 5.12 Regional distribution of damages caused by the 2010 Xynthia windstorm



5.2.2.2 Industrial direct damages

The upper-left map (a) depicts the regional distribution of direct damages to industrial capital. France was the worst affected country with 75% of industrial direct damages (ca. €1.9 billion). The distribution of damages to industrial capital among other countries is as follows: Germany (16%), Spain (6%), and Belgium (3%). The remaining 1.3% is distributed among Italy, Luxembourg, The Netherlands and the United Kingdom.

The worst affected region was Île de France, accounting 29% of the industrial damages in France.

5.2.2.3 Residential direct damages

The upper-right (b) map shows the direct damages to residential capital. Again, France was the most affected country accounting 70% of the total damage in this category (ca. €1.2 billion). The three most affected regions are localised within France: Île de France with 29%, Rhône-Alpes with 11% and Nord - Pas-de-Calais with 6% of French residential damage respectively. Other seriously affected regions outside France are Düsseldorf (ca. €47 million) and Darmstadt (€40 million) in Germany, and Comunidad de Madrid in Spain (ca. €36 million).

5.2.2.4 Indirect damages

The regional distribution of the indirect damages is presented in lower-left corner (c). The most affected country is France, accounting for 62% of total indirect damages (€3 billion), with Île de France being the most affected region accounting for 26% of national indirect damage (€780 million). The second most affected region is Rhône-Alpes in France (€344 million) accounting for 12% of national indirect damage. The most affected regions outside France are Düsseldorf (€124 million) in Germany, and Comunidad de Madrid (€120million) in Spain.

5.2.2.5 Windstorm footprint

The regional distribution of the flood footprint of the event is presented in the lower-right map (d). France concentrates the largest proportion of damages, with over two thirds of total flood footprint (€6 billion). Germany accounts for 18% (€1.7 billion) of the total flood footprint, Spain with 7% (€610 million), Belgium 3% (€307 million), Italy 2% (€180 million), The Netherlands 1.7% (€154 million), The United Kingdom 0.7% (€61 million), and Luxemburg 0.5% (€41 million).

For comparative purposes with the respective national GDPs, windstorm Xynthia's footprint in France represents 0.31%, in Luxemburg 0.1%, Belgium 0.09%, Germany 0.07%, Spain 0.06%, The Netherlands the 0.03%, Italy 0.01% and in the United Kingdom 0.004%.

The three most affected regions are Île de France with 28% (€1.7 billion) of national windstorm footprint, Rhône-Alpes with 11% (€689 million), Nord Pas-de-Calais with 6% (€351 million), and Pays de la Loire with 5.8% (€350 million), all of them located in France.

5.2.2.6 Sectoral distribution

This section presents the distribution by economic sector of the direct damages to industrial capital and the indirect damages for all the affected regions.

Figure 5.13 Distribution of direct and indirect damage by economic

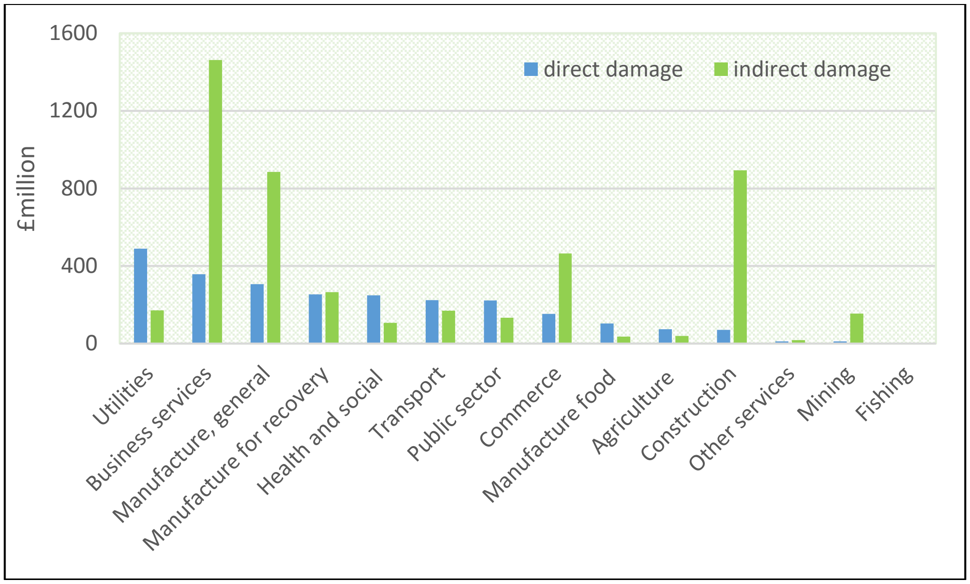


Figure **5.13** depicts direct and indirect damage organised by industry sector for all affected regions. The most affected sectors by direct damage are Utilities, Business services and Manufacture general sectors. These three sectors concentrate 46% of the total direct damages (€1.1 billion). Regarding indirect damages, the Business services sector is the worst affected accounting for 30% of total indirect damages (€1.5 billion). Other sectors with losses over €800 million are Construction (€892 million) and Manufacture general (€884 million). These three sectors concentrate 68% of the indirect damage.

5.2.2.7 National distribution of damages by industrial sector

Figure 5.14 National distribution of direct and indirect damage by industrial sectors

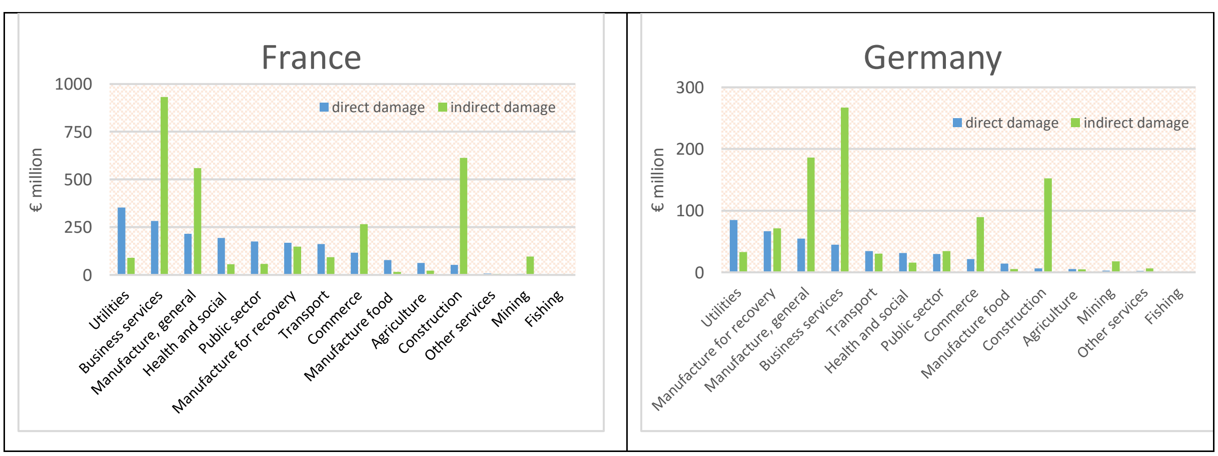


Figure 5.14 shows the national distribution by economic sectors of direct and indirect damages. In all countries, the sector that suffer the greatest direct damages is Utilities sector. In the case of indirect damages, the three most affected sectors are Business servicers, Construction and Manufacture General.

In France, direct damages to industrial capital account for €1.9 billion while indirect damages account for €3 billion. Around 43% of direct damages occur in Utilities (€353 million), Business services (€282 million) and Manufacture general (€216 million) sectors. On the other hand, 71%

of indirect damages are concentrated in Business services (€931 million), Construction (€613 million), and Manufacture general (€559 million) sectors.

In Germany, direct damages to industrial capital amount at €400 million and indirect damages account for €914 million. Three sectors, Utilities (€85 million), Manufacture for recovery (€66 million), and Manufacture general (€55 million) concentrate 52% of direct damages. Two thirds of indirect damages are concentrated in Business services (€267 million), Manufacture general (€186 million) and Construction (€152 million) sectors.

Direct damages in Spain account for €151 million, while indirect damages account for €360 million. Direct damages in Utilities (€32.6 million), and Manufacture general (€20.5 million), representing the 35% of the total loss. In comparison, Business services, Construction, and Manufacture general concentrate around two thirds of indirect damages (€226 million).

Belgium, Italy, Luxemburg, The Netherlands and The United Kingdom together account for 4% of direct damages (€100 million), and 12% of indirect damages (€570 million).

5.2.2.8 Sensitivity Analysis. Xynthia Windstorm 2010

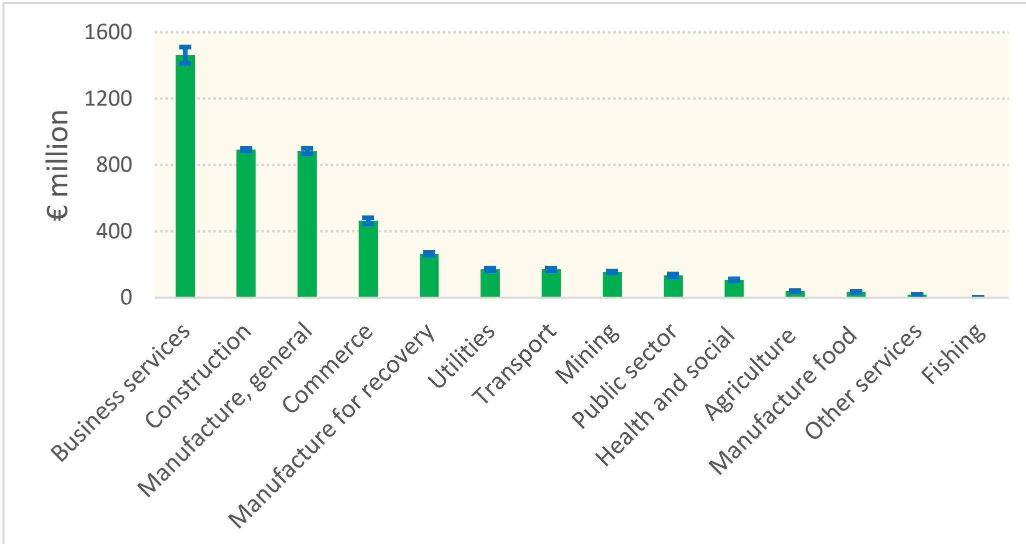
A sensitivity analysis was carried out on the model parameters related with the damage curve for labour, and behavioural changes in final demand.

The sensitivity analysis comprises the upwards and downwards variation of 30% of the parameters in intervals of 5%.

Related to final demand, the variation of parameters comprises the decreased proportion of consumption in non-basic products. While for labour, the variation of parameters comprises the proportion of labour not available for traveling, and the proportion and time of labour delayed by transport constraints. Here are presented the results of a global sensitivity analysis, this is, the results of variations in all parameters at the time. This is due to changes in final demand parameters gave non-significant changes in results.

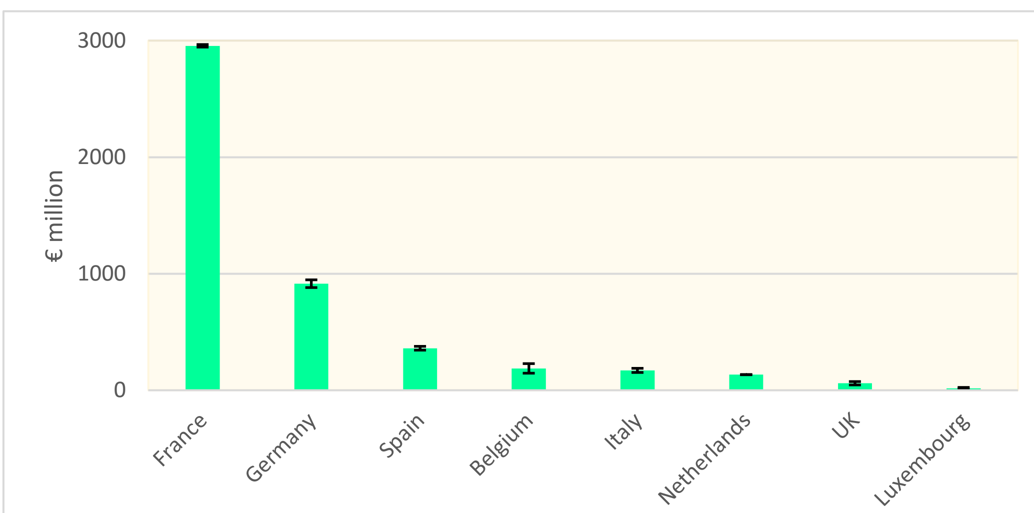
The error bars in Figure 5.15 show the standard error by industry sector, from the sensitivity analysis. In average, the standard error is 5% different from the mean values. The maximum error, in relative terms, is found in the Manufacture Food sector, which represent a deviation of 7.5% regarding the mean values. The maximum error, in absolute terms, is found in the Business services sector, which represent a deviation of €48 million (34% of total standard error). The standard error of the overall result (the variation in total indirect damage for all sectors in all regions) is 3% different from the mean (± €141 million).

Figure 5.15 Sensitivity analysis by sector



In Figure 5.16, the error bars represent the variation given by the standard error from the sensitivity analysis, by country. It can be noted that the distribution of the error is more heterogeneous than by sector. This is mainly due to the variation is distributed among less categories. The maximum error, in relative terms, is found in the UK, which represent a deviation of 11.3% regarding the mean values. The maximum error, in absolute terms, is found in France, which represent a deviation of €41 million (29% of total standard error).

Figure 5.16 Sensitivity analysis by country



The sensitivity analysis shows that the model is relatively stable, and the results can be considered robust, as variations in the model parameters causes less than proportional changes in results. In this case, a variation of ± 30% in the parameters values results in a standard error equivalent to 3% of the mean value of the total indirect damages of the event.

5.3 Summary

The results in this chapter show the regional distribution of the direct and indirect damages for two past extreme climatic events. The single-regional flood footprint model, was applied to multiple regions, allowing consideration of the total economic impact of the disaster, comparison of the differences in economic structure among regions, as well as the differences in impacts from two different natural hazards. This analysis becomes especially useful in a context such as that of the European Union, where adaptation policies seek 'umbrella' strategies to reduce the climatic risk to all the affected regions.

The use of damage functions allowed the analysis of a disaster different from a flood. The windstorm damage functions were developed in an analogous way to the flood damage functions. While the basic process is the same, additional parameters can be considered, such as wind velocity. This shows that different types of disaster can been analysed through the flood footprint model whenever the damages of a disaster can be expressed as a proportion of industrial capital or labour force productivity.

The results also add to the evidence that indirect damages account for a considerable proportion of the total economic costs of a natural disaster. For the 2009 Central European floods, the indirect damages represent 46% of total damages, while for the Xynthia windstorm the indirect damages represented 53.3% of total damages. It also reinforces the results of other researches (Stéphane Hallegatte, 2008; E.E. Koks et al., 2014) by indicating that the proportion of indirect damages in the total impact of a disaster increases in direct proportion with the size of the damage.

In summary, the flood footprint modelling was methodologically extended with two purposes. First, the incorporation of the capital matrix improves the methodology by adding theoretical consistency, as it provides a clear transition between the investment to restore the capital stock, and the increase in productive capacity that derives from this.

Secondly, the flood footprint model was extended to assess the total direct and indirect damages of multiple regions. This improves the understanding of the total effects of a disaster and increases the adaptability of the model to undertake more realistic analysis and cases.

The use of damage functions increases the flexibility of the model to consider a wide range of disasters. It also allows the incorporation of research results from flood modelling and other hazards, which creates the potential to predict damages for projected future disaster events.

It should be noted that at this point the model does not consider the interregional trade, which is the main contribution of the model used for the case study in the next chapter, the Multi-Regional Flood Footprint model (section 3.5).

Chapter 6 Multi-regional flood footprint analysis: case study of Rotterdam, The Netherlands.

The purpose of this chapter is to fulfil Objective 4, which is the empirical application of the multiregional flood footprint model to the appraisal in multiple regions, which allows examining the cascading effects beyond physically impacted regions.

Since different economies as well as societies are highly connected in the globalized world, any small-scale damage in one country may be amplified and cascaded to wider economic systems and social networks.

The previous chapters have shown how the direct damages of a climate extreme event triggers a series of indirect costs to the regional economy. However, given the economic interconnectedness with other regions, it is expected that the direct damages trigger indirect effects through these linked economies. The indirect damages that spill over other countries is rarely considered in impact evaluations. The flood footprint concept could capture these effects.

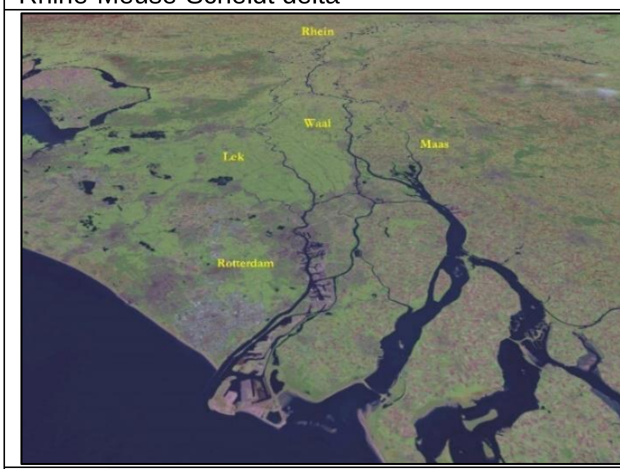
This chapter applies the multi-regional flood footprint (MRFF) model from Chapter 3.3 (Methodology for the multi-regional Flood Footprint model) as an extension of the flood footprint model, to consider, in addition to the regional direct and indirect damages, the indirect damages to regions that are economically interconnected with the impacted region. The MRFF model provides the ideal methodology for assessing the total economic damages that are spread over a multiregional scale. This is one of the few methods to assess the indirect cascaded damages to other economies outside of national boundaries. The result of the case study suggests that adaptation strategies should be considered as global issues, instead of local problems, as they have traditionally been considered within climate change economics (IPCC, 2007).

This chapter shows the development, application and results of the MRFF model to a projected flooding scenario in the city of Rotterdam, The Netherlands. The economic importance of the city of Rotterdam, not just for The Netherlands but also for the whole Europe; and the susceptibility of the area to flooding events result in a relevant case study upon which to apply the flood footprint assessment in a multi-regional context.

6.1 Rotterdam

Rotterdam is one of the most densely populated areas in The Netherlands with 1.6 million inhabitants in an area of 1,130 km^2. It is also one of the most important economic cities in the country and Europe, as it hosts the largest port on the continent and the 10th largest in the world. The city of Rotterdam is located on the delta of the Rhine-Meuse-Scheldt River, in the Midwestern Netherlands. Owing to these characteristics, climate change implies an increasing flooding risk as a result of the expected sea level rise and an increase in the frequency of sever rainfall events (Jeuken, N. Slootjes, Gauderis, & Vos, 2013). Figure 6.1 Location of the metropolitan area of Rotterdam shows the location of the city of Rotterdam in relation with the Rhine-Meuse-Scheldt delta, and the location of the 24 municipalities that constitutes the wider economic area of analysis in this chapter.

Figure 6.1 Location of the metropolitan area of Rotterdam

Rhine-Meuse-Scheldt delta	Metropolitan area or Rotterdam
	
Source: Wikimedia Commons (2017. c)	Source: Commons Wikimedia (2017. d)

These socioeconomic and geographical characteristics give rise to climate change risk in four areas. The first area at risk is identified as the foreshores of the River Rhine, where major harbour areas are located. Flooding in this area would cause shortages of imports to the city, but also to the country and the entire Europe. The second risk hotspot is located behind the flood defences, where most urban activities take place, such as houses, businesses, real state, etc. This puts the life of civilian population at risk, and it would cause businesses interruptions during a flooding. The third area of risk is related to interruptions in critical infrastructure behind the flooding defences, such as hospitals, power stations, roads, water treatment plants, etc. Flooding adaptations strategies are urgent in this area, as the functioning and survival of the socioeconomic system depends on this infrastructure functioning during the disaster aftermath.

Finally, the fourth area at risk are the agricultural and rural structures lands bordering the urban areas (BASE, 2016; Delta Programme Commissioner, 2017).

To cope with the climate change risk, the city government has implemented major adaptation strategies focused on reinforcing the prime flooding defence system from the river tributaries in the metropolitan area. The system comprises the main water system and the urban water system. The first includes flooding defences such as dikes, storm surge barriers, pumping and drainage. While the former involves the sewage system, there are local retention possibilities on parks, squares and roofs, and improvements to urban water management in general.

The goal of the adaptation strategies is to provide sufficient flood prevention in the metropolitan area of Rotterdam for future decades, given the expected increase in river discharge due to climate change, and the risks associated with socio-economic development (Delta Programme Commissioner, 2017).

6.1.1 Historical flood risk context

The western area of The Netherlands, where the city of Rotterdam is located, has been historically prone to flooding events. The worst flooding that the city has experienced dates to 1953 when the Rhine-Meuse-Scheldt delta overflowed in the south of Rotterdam causing a major disaster that resulted in the loss of life of 1,863 people in The Netherlands. After the event, the government decided to construct the delta flooding protection system called Dutch Deltaworks, which includes a series of dykes, levees, storm surge barriers, dams and sluices. Recent flooding includes the events of 2006, during which the city experienced record precipitation levels, accumulating 200mm within a month. This leaded to severe flood damages in the Rotterdam city area. Generally, it should be considered that the rainfalls events in winter are especially intense, increasing the flood risk during those months.

The main climate change risk for Rotterdam is the sea level rise. During the last century, the North Sea rose 200mm, with a growth rate of 3mm per year between 1993 and 2014. The combined effects of climate change and rapid urban development have exacerbated the risk by a factor of seven. Even without climate change, the growth of urban settlements in vulnerable areas to flooding would have increased the level of risk.

The circumstances lead the creation of the Delta Programme in 2010 by the Dutch parliament, to provide adaptation strategies to ensure the resilience of the country during this century.

Rotterdam is an essential part of this programme, and the case study here is bounded by the general objectives in the programme (BASE, 2016).

6.1.2 Urban planning context

Located in the delta of the Rhine-Meuse river, life of Rotterdam has since its beginnings been cantered on its harbour. Later, industrialization brought an economic boost to the city as a result of increased commerce through its harbour, until the city centre suffered extensive bombing during the Second World War. However, post-war reconstruction gave rise to a new economic growth, repositioning Rotterdam as one of the largest ports in the world.

However, economic development came with important developments from a flood risk perspective, with renewed investment in flooding defences; but a concurrent increase in socio-economic risk owing to changes in population density and economic activity intensity (BASE, 2016).

6.1.3 Institutional context

The responsibility for adaptation policies regarding flood risk management fall upon the government at different levels. The river tributaries and seashores are mainly the responsibility of national government, while the responsibility of the urban water system falls mainly with the municipality, alongside partial participation of local boards. Other stakeholders such as the port authority, civil organisations and/or large companies may influence decisions regarding the state of the system. Finally, the effectiveness of public adaptation policy may be influenced by citizen decisions (BASE, 2016; Jeuken et al., 2013; Rotterdam Climate Initiative, 2014).

6.1.4 Data

Rotterdam was chosen as the case study to apply the multi-regional flood footprint appraisal, due to the susceptibility of the city to flooding, giving the geographical and meteorological circumstances and the increased risk as a result of projected climate extreme events and socioeconomic development. As in previous cases, the data to carry out the flood footprint analysis is organised into two sets: a) monetary information about the disaster’s destruction, and b) information on the economic infrastructure and, in this case, commercial networks.

6.1.5 Disaster information

The information on flood projections and damages is provided by the Deltares research institute[29]. The flood projection is an average of several future scenarios for Rotterdam developed within the Flood Risk in The Netherlands (Veiligheid Nederland in Kaart – VNK2) project[30]. In general, the project analyses and provides estimation on flood risk in The Netherlands. The scenarios consist on a range of future climate projections combined with a range of socio-economic scenarios. In general, the climate scenarios run from moderate to severe climate change projections, while the socioeconomic scenarios range from low to high socioeconomic development estimations (VNK2 project office, 2012). The climate scenarios are in line with the projections called RCP6.5 and RCP8.5 described in the 5th Assessment Report of the (IPCC, 2013). The main foreseeable consequence of climate change in these scenarios, related to the flood footprint analysis, is an increase in flood risk attributable to higher mean river discharges, increased surface flooding and problems in sewage as a result of extreme rainfall events.

The estimation of a flood's direct damages under the climate-socioeconomic scenarios are based on information from the *Hoogwater Informatie Systeem*, within its *damage and victims'* module (*Schade en Slachtoffer Module.* HIS-SSM). The HIS-SSM system translates the flooding projection of a specific return period event into direct economic damage using depth-damage functions (BASE, 2016).

The data for the flood footprint analysis in Rotterdam considers a 1:10,000 years return period flood for the described average projection of future climate-socioeconomic scenarios. The estimations of damages consider a combined outline with both sides of the river flooded based on multiple breach locations of the levee. As data form the HIS-SSM is for the year 2000, the values are updated based on information in the Dutch project *Flood Protection for the 21st Century* (in Dutch: Waterveiligheid 21e eeuw, WV21)[31].

The costs of projected direct damages are provided in US$ millions at 2011 prices, for 49 categories of physical assets, such as roads, airports, urban areas, etc. Using a concordance

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[29] Deltares institute: https://www.deltares.nl/en/

[30] VKN2 project: https://www.helpdeskwater.nl/onderwerpen/waterveiligheid/programma'-projecten/veiligheid-nederland/english/flood-risk-the/

[31] WV21: https://www.helpdeskwater.nl/onderwerpen/water-ruimte/klimaat/factsheets/waterveiligheid-21e/

matrix, the information on direct damages is distributed among 35 industrial sectors to match with the economic information in the MRIO tables.

6.1.6 Economic information

The main source of economic data is the World Input-Output Database[32] (WIOD) (Timmer et al., 2015). The WIOD provides a time-series World Input Output table (WIOT) with data available for the years 1995- 2014. The WIOT used in this case study is for 2011, as this is the year of the latest release of other socio-economic accounts available within the WIOD project, and needed for the analysis, such as capital stock and employment data. The WIOT contains information for 40 countries (which includes the 27 EU member states and 13 other countries), including a Rest of the World (RoW) region.

The table is a compendium of national IO tables constructed by the national accounts, interlinked throughout the international trade of intermediate and final demand. All national tables include35 industry sectors, following the International Standard Industrial Classification (SIC) of All Economic Activities Rev.3, by the United Nations Statistical Commission (UNSD, 2014). Owing to this, the inter-regional matrices are squared matrices of a range of 35 (industries). The WIOT also provides the information of final demand accounting the region and industry of origin, as well as the region and the category of final consumption. The categories of final consumption include households' final consumption, final consumption by non-profit organisations, government expenditure, gross fixed capital formation, and changes in inventories.

When the information in the WIOT is read row-wise for a specific industry (i) in a specific region (r), it depicts the product needs from industry i from region r that is used as input for production in all sectors in all regions. In other words, the typical element [z_{ij}^{rs}] of the multiregional inter-industrial transactions, $\boldsymbol{Z^R}$, indicates that the amount of product z that is produced by industry i in region r and is going to be used by industry j in region s. For the final demand, the typical element [$f_{i,k}^{rs}$] tells us the amount of product f that is produced in industry i in region r that is demanded in region s to be consumed in the final demand category k. In other words, it explicitly discloses the destiny of exports when the region of destiny is different from the region of origin.

[32] WIOD: http://www.wiod.org/new_site/data.htm

When the table is read column-wise, they provide information on the input requirements of industry j of products of other sectors, from local and external regions, i.e. the element $[z_{ij}^{rs}]$ indicates the amount of input z from industry i produced in region r that is needed in industry j in region s to realise the production of industry j in region s, x_j^s. It also includes the payments to the productive factors (or the VA) and other transactions for production such as taxes and subsidies. For the case of final demand, the tables explicitly disclose the information about the origin of imports for final consumption. Thus, element $[f_{i,k}^{rs}]$ indicates the final demand of products in the category k in the region s that comes from industry i in region r.

The section of the socioeconomic accounts of the WIOD also provides information on capital stock and employment, for the same classification of sectors and regions as in the WIOT.

6.1.7 Economic data on Rotterdam

For the Rotterdam case study, to account for damages at the city level the standard method to regionalise the IO tables was applied to obtain the IO tables, i.e. the AFLQ regionalization technique. The economic information to assess the city's economic size was obtained from the statistical office of the EU, Eurostat[33]. Information on GVA and employment by industry was obtained at NUT2 level from the database used in the multiple single-regional analysis (NEG database). It should be noted that the NUTS2 information is for the region Zuid-Holland (South Holland), which incorporates the city of Rotterdam. This data was used for the sectoral distribution of intermediate and final demand. The industry aggregation in this dataset is for 14 industrial sectors so a concordance matrix was used to match with the 35-sector disaggregation in the WIOD.

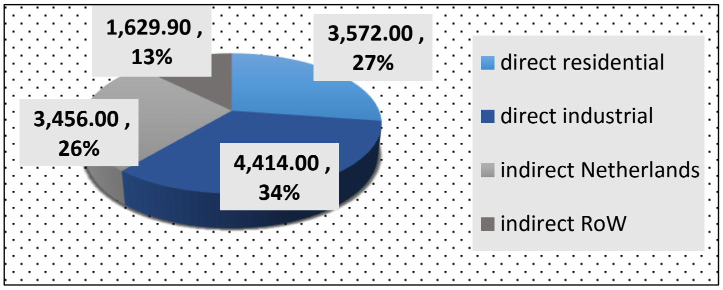
6.2 Results. Multiregional Flood Footprint assessment

This section presents the results of applying the multiregional flood footprint model to a projected flood event in Rotterdam.

[33] http://ec.europa.eu/eurostat/web/main/home

6.2.1 Direct and Indirect damage

Figure 6.2 Multiregional Flood Footprint (US$ million)



The Figure 6.2 shows the distribution of the damage in two dimensions: the type of damage (direct or indirect) and the region (national or international).

According with the analysis, the total Flood Footprint of the projected event accounts for US$13.1 billion in total, which for comparative purposes represents over 1% of The Netherlands GDP for the year 2011. The direct costs accounts for US$8 billion (ca. 61% of the Flood Footprint), from which US$3.6 billion are for residential damages, while US$4.4 billion are for industrial damages.

The indirect damages (the missed production due to the physical damage to industrial and infrastructure capital) represent US$5.1 billion (ca. 39% of the Flood Footprint). Considering the regional allocation of the indirect damages, US$3.5 billion (ca. 68% of indirect damage) was production lost to The Netherlands' economy. The impact of the flood spreads to other national economies causing a loss of US$1.6 billion (ca. 32% of indirect damage). The considerable contribution of indirect damage to the Flood Footprint that is experienced by the rest of the world in of note. The ratio of total direct damage to total indirect damage is of 1:0.6, i.e. for each unit of damage to physical assets there are 0.6 additional units of indirect costs across The Netherlands and the rest of the world.

The impact in other economies through international trade is also considerable. This represents over 12% of the entire Flood Footprint. It should be noted that the direct damages to Rotterdam are expressed as damages for The Netherlands, as the interregional links in the WIOT data are given at national level. The regional and sectoral distribution of the indirect damage to other economies provides insight to vulnerable links in the international value chain.

6.2.2 Recovery path

Figure 6.3 Recovery path

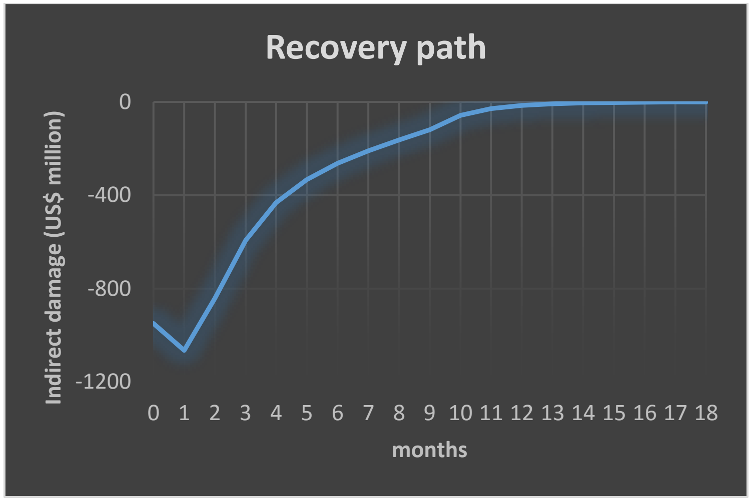


Figure 6.3 shows the overall Flood Footprint recovery curve. This is certainly influenced by the model design, although it corroborates with the literature which suggests a fast recovery for the first months in the aftermath of a disaster (when resources from emergency plans and international aid are allocated for reconstruction), and a slowing down when approaching the pre-disaster level. It can be noted that even when the model predicts a recovery of 18 months, the production is at 98% of recovery to the pre-disaster level after the first year. The remainder of the recovery time allows market imbalances to readjust.

It is important to note that one month after the disaster there is an additional decrease in the productivity. As the indirect damage in month zero represents the productivity decrease associated to the direct damage, which only affects the national economy, the additional decrease in production is explained by the loss of productivity outside The Netherlands. This fact reinforces the relevance of the multi-regional evaluation of the Flood Footprint, in considering the broader damages from a flooding event that spread out through economic interconnectedness.

6.2.3 Regional distribution

Figure 6.4 *Indirect damage by country*

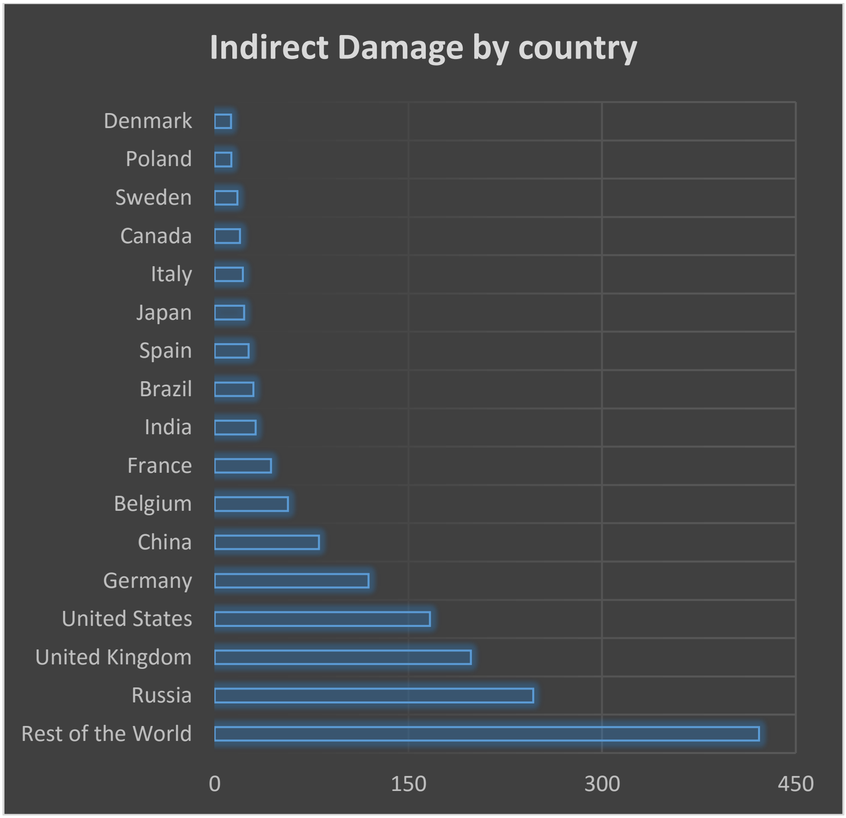
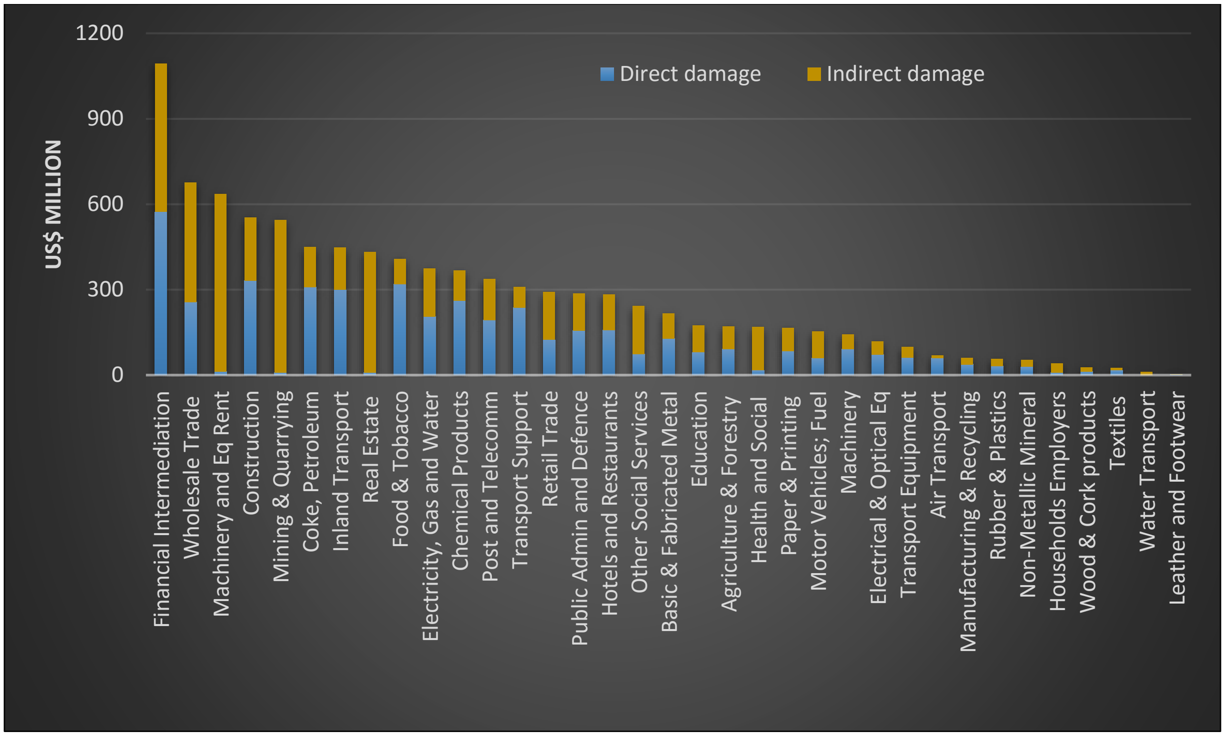


Figure 6.4 shows the regional distribution of indirect damages in the most affected countries. The distribution of these damages is correlated with the economic trade of The Netherlands with other countries. The damage for the Rest of the World regions is the summation of the indirect damage in the remaining 154 countries of the world. The five most damaged countries represent 16% of the total indirect damages and 50% of the indirect damage outside The Netherlands.

6.2.4 Sectoral distribution

Finally, Figure 6.5 shows the sectoral distribution of both industrial direct damage and indirect damage, in The Netherlands. In general, the indirect damage within The Netherlands sustain a relation of 1:0.8 with the industrial damage in Rotterdam.

Figure 6.5 Flood Footprint in The Netherlands



The most affected sector from direct flooding impacts is the Financial Intermediation sector, accounting for US$573 million (ca. 13% of direct damage); followed by Food, Beverages and Tobacco; Coke, Refined Petroleum and Nuclear Fuel; and Construction sectors, with damages over US$300 million.

Regards to the indirect costs, it is again the Financial Intermediation sector that contributes the most to the damage with US$417 million (ca. 12% of indirect damages within The Netherlands). The other three most affected sectors are Real State activities (US$395million); Renting of Machinery & Equipment and Other Businesses (US$362million); and Wholesale Trade and Commission Trade sectors (US$328million), which together accounts for over 30% of the indirect damage in The Netherlands.

It is notable that the distribution of the indirect damage is grouped mostly in the businesses and professional sectors, which account for over 50% of the indirect damage in The Netherlands.

6.2.5 Sensitivity Analysis

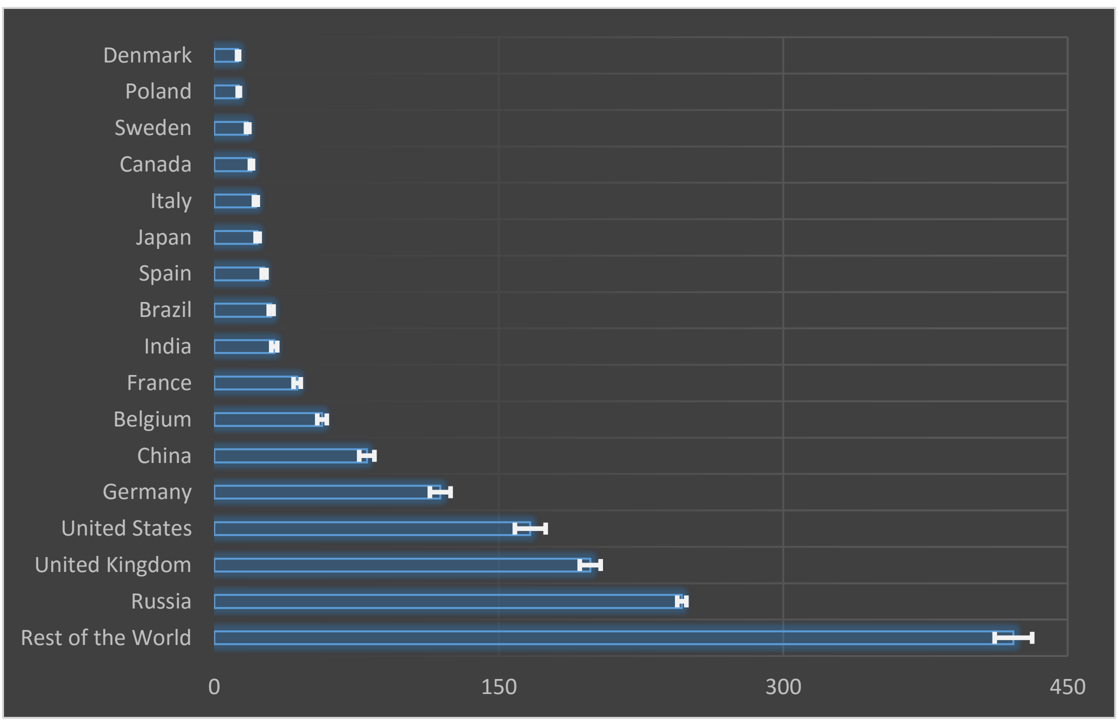
This section presents the sensitivity analysis over model parameters. A variation of ±30% in intervals of 5% was applied for labour parameters and changes in final demand. It is only presented the global sensitivity analysis, as the local variation for each of the parameters shows non-significant results.

The Figure 6.6 shows, in the error bars, the variation in the indirect damages by country, outside the Netherlands. The biggest variation, in absolute terms, is found in the Rest of the World. This was expected, as it encloses the variation of 154 countries. This represent a 2.3% variation (£ 9.8 million) regarding the reference value. However, the biggest variation in relative terms is found in the effects to The United States, which represent a variation of ± 5% regarding the reference value.

It should be mentioned that results in the Netherlands under the sensitivity analysis represented a variation of ± 5.4%.

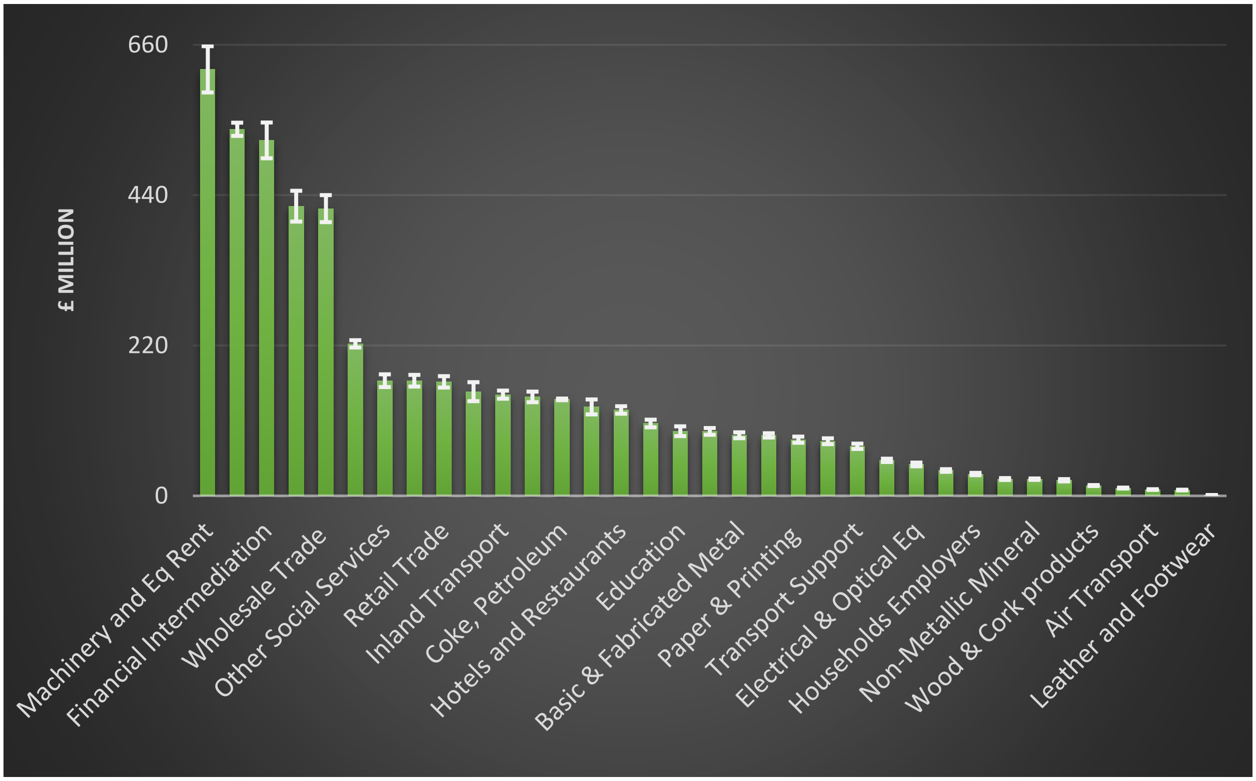
The total variation of overall results is ± 4.7% (£ 241 million) from reference values.

Figure 6.6 Sensitivity Analysis by country



The Figure 6.7 shows, through the error bars, the sensitivity analysis' results by sector. The highest variation, in relative terms, is found in the Health and Social sector, with a 9.1% (£14 million) variation from the mean values. On the other hand, the highest variation in absolute terms is found in the Machinery and Equipment Rent sector, which represent a variation of £34 million (5.4%).

Figure 6.7 Sensitivity Analysis by sector



As in previous analytical chapters, where the sensitivity analysis has been applied, it can be noticed that the results vary less that proportional, regarding the parameters variation. This indicate the model is stable, and the results, under the considered assumptions and data, can be considered robust.

6.3 Summary

This chapter presented the multiregional extension of the flood footprint model. The projected flood scenario in Rotterdam considering climate change and socioeconomic development, offered the perfect case study to assess the consequences of a projected major flood. This is due to the particular flood risk imposed to the region by climate change, and due to the relevance of the city's economy to the national economy and wider economic networks, mainly in the European Union.

Once again, the flood footprint assessment framework took advantage of the depth damage functions, which is becoming the standard practice in the assessment of flooding damages. This allowed for the economic impact assessment of future scenarios, as allow the consideration of different variables, such as economic growth, socioeconomic development, climate change, etc. This makes the MRFF a useful tool for the evaluation of the consequences of climate extreme events related to climate change.

Regarding the modelling extensions, the multi-regional version of the FF model constitutes an important contribution towards improved understanding of the costs of natural disasters, as it accounts for the total flooding effects beyond the flooded region. The transmission mechanisms of the effects from the affected region to the rest of the world is modelled as the reduction of inter-industrial inputs that the non-flooded regions use from the flooded region, i.e. it accounts for the backward effects of constraints in intermediate demand. Due to the way in which the mechanisms of transmission of the effects were modelled, it is expected to have effects in the same direction, i.e. economic losses in the flooded region would trigger economic losses in connected regions. It must be noted, however, that the MRFF model needs further development, and one direction is to consider the effects of imports, which have been shown to bring economic benefits in terms of employment and higher demand to those regions supplying the inputs for reconstruction and final demand that cannot be supplied internally in the flooded region (Stéphane Hallegatte, 2008).

The analysis reveals the relevance of economic interconnectedness, and how damages from climate extreme events in a region can spread over several regions. This should be taken into consideration in adaptation policy planning, especially in generating integrated adaptation policies across different countries. In climate change economics, it is generally argued that mitigation of climate change should be a global issue, while adaptation to the consequences of climate change is more a local issue. The type of analysis presented in this chapter offers evidence to question if adaptation to climate change should be local, as the successful adaptation strategies in one region (or reducing the costs of flooding in the case presented here) would benefit wider economic networks. In summary, a multi-regional strategy for adaptation policies would decrease the potential damage in highly interconnected economies.

Chapter 7 Flood footprint analysis and application in a Blue-Green infrastructure approach: case of Newcastle city

The purpose of this chapter is to fulfil Objective 3, which is to Inter-connecting flood footprint model with engineering models to enable better capture of physical damage and the analysis of projected scenarios; and Objective 4, which is the empirical application of the flood footprint model to the appraisal of the benefits of a climate risk management option.

This chapter presents the adaptability and applicability of the flood footprint model within a hybrid method to assess the benefits of strategies for flood risk management, which in this case is the implementation of blue-green infrastructure (BGI).

This is possible through the integration of a flood model, a multi-benefits evaluation model based on Geographical Information Systems (GIS), and the application of the flood footprint assessment framework.

This hybrid approach assesses the benefits of applying hypothetical BGI in the city of Newcastle for six return period events.

For each return-period event, the flood model estimates the water depth distribution in the area where BGI would take place. The GIS based model estimates the direct costs of the flood (among other type benefits, e.g. environmental, social, etc.). Finally, the flood footprint estimates the indirect costs for the whole city for both BGI and the current 'grey' infrastructure (GI) scenarios. Then the total economic costs (or flood footprint) are estimated for each return-period flood, for each infrastructure scenario. Finally, the economic benefits (or avoided costs) of BGI are defined, for each return-period event, as the difference of total damages under GI scenario, minus total damages under BGI scenario. If damages under BGI scenario are smaller than damages under GI scenario, the benefits will be positive.

The results show that direct and indirect damages are lower under BGI, for all return periods. They also suggest that the proportion of indirect damages in the flood footprint increases as the intensity of the events increase, and they increase more than proportionately for GI. This suggests that BGI implies benefits for all return periods, and the biggest share of benefits comes from avoided indirect damages for higher return period events.

It must be noted that the data from the GIS model was generated with the purpose to demonstrate a concept, and provides a conservative estimation of extent of the potential flood direct damage. The overall results are influenced by this.

It must be also considered that the GIS model was constructed to prove a conceptual method to assess the benefits of BGI, and not for actual estimation of results at this stage. Thus, the results of the economic benefits should be considered under these circumstances.

7.1 BGI for flood risk management

The sustainable development of societies around the world lies in their capacity to adapt to climate change. Adaptation strategies in cities deserve particular attention as cities agglomerate more than half of the population worldwide, with this proportion expected to reach 66% by 2030 (IPCC, 2014; United Nations, 2014).

The Intergovernmental Panel on Climate Change (IPCC) defines *adaptation* as *'The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects'* (IPCC, 2014). Adaptation strategies must be oriented to reduce the risk of climate change consequences such as intensified floods, windstorms, hurricanes, droughts, etc. Adaptation strategies must also be targeted to reduce one or more of the elements of risk; hazard, exposure, and vulnerability.

In the UK, floods are a recurrent phenomenon owing to the nature of its geography and climate. Moreover, the demographic and socioeconomic composition increases exposure to the harmful consequences of floods (over 80% of the population live in urban areas) (Office for National Statistics, 2013). The expected future increase in these factors, due to projected changes in the climate and the growth of urban population, increases the vulnerability of cities in the UK (IPCC, 2014).

Cities are particularly vulnerable to floods due to high proportions of impermeable surfaces and reliance on predominantly traditional piped grey infrastructure (GI) that interrupts the natural cycle of water. Existing infrastructures for flood risk management is put under pressure during heavy rainfall events and storm surges, increasing the chance of exceedance and consequential flood risk. The situation urges for adaptation measures with new approaches that integrate urban water and flood risk management while permitting sustainable development of the cities at risk.

Within this context, the Blue-Green Cities (BGC) approach proposes the incorporation of BGI, such as swales, green roofs and walls, raingardens and wetlands into urban environments to promote the recreation of a more naturally-oriented water cycle. The multifunctional nature of BGI suggests, that at a strategic level, it may assist diverse policies oriented to the enhancement of flood risk management, climate change adaptation, and improvements to the quality of the environment, citizens' health and wellbeing (Hoyer, Dickhaunt, Kronawitter, & Weber, 2011).

To evaluate the benefits of BGI over traditional grey strategies for flood risk management, we must define first typical GI strategies to manage flood risk and the associated issues when coping with increasing flood events. GI refers to in-built infrastructure, such as pavements, roads, bridges. Regarding flood and water management, typical grey engineering approaches include sewerage mains, tunnels, flood barriers and walls, dam construction, and river defences. However, these options alter the natural cycle of water by preventing the infiltration into the subsoil, evapotranspiration and natural migration of river channels. Moreover, the heat island effect created by cities may alter the air circulation, which also generate alterations in climate and water-cycle patterns.

In contrast, BGI and sustainable drainage systems (SuDS) are able to attenuate, infiltrate, store and generally slow the flow of water through drainage systems. When in place, BGI reduces the pressure on existing grey infrastructure to transfer and treat storm water (and combined flows), improving the performance of existing piped systems and waste water treatment plants, and reducing the severity of floods (Josh, Ashley, & Steve, 2011). In addition to the benefits associated with reduced flooding damages, BGI also creates a wide range of direct benefits to the environment (e.g. reducing heat, improving water quality, carbon sequestration, improving wildlife and biodiversity) and society (e.g. increasing opportunities for recreation, improved aesthetics and enhanced health and wellbeing) (Lawson et al., 2014; O'Donnell, Woodhouse, & Thorne, 2017).

Owing to the above, the BGC approach represents a promising adaptation option for flood risk management and policies for climate change adaptation, with a potential of delivering multi-dimensional benefits. However, the development of a BGC requires a considerable amount of investment in financial and social resources, so that the decision must be based on a sound evaluation of the potential net benefits of different approaches.

Moreover, as the flood footprint framework suggests, the reduction in flooding direct damages through BGI would have positive effects in wider areas beyond the site of intervention, owing to the reduction in indirect damages. These benefits may not necessarily be included in traditional cost-benefit analyses, which suggests that the benefits of BGI may frequently be underestimated reducing thus opportunities for implementation. Therefore, the economic assessment of the ability of BGI to reduce flood risk would serve as a tangible basis on which investment decisions can be built on.

For this purpose, this chapter presents the results of a hybrid method that merges a GIS Multiple Benefits Toolbox (MBT) and the Flood Footprint model, to quantify the potential economic benefits (or avoided costs) of flooding risk management throughout BGI.

The rationale to use this methodology lies on the proposition that BGI reduces flood risk parameters, such as depth, velocity and flood extent; which would induce, during flooding circumstances, additional benefits related to hazard regulation. The economic benefits assessed here are derived from the reduction in costs from flood damages.

The work presented here evaluates the flood footprint of six different return-period events under GI and BGI scenarios within the City of Newcastle, UK.

The City of Newcastle was selected as a demonstration case study due to significant pluvial flood risk and relatively recent inundation events. For instance, in the summer of 2012 the city suffered one of the worst floods in a century. According to Newcastle City Council the 2012 summer flooding caused direct damages of £34 million in the city (Newcastle City Council, 2013) and the flood footprint assessment estimated that indirect damages would represent an additional £44 million burden.

7.2 Methodology

This section explains the general rationale of the GIS model and the delivery of direct damages for each case that serves as input for the single regional flood footprint model to assess the indirect damages. This section is based on (Morgan & Fenner, in press). The version of the flood footprint model applied for this case study is the single-region flood footprint model, developed in Chapter 3, so that it is not reproduced here.

7.2.1 The Multiple Benefits Toolbox

The Multiple Benefits Toolbox (MBT) is a model based on a GIS to assess the multiple-dimensions of the benefits derived from incorporating BGI assets into an urban environment. The MBT integrates the results of a hydrodynamic model to assess the multiple-benefits, such as the noise reduction, carbon sequestration, air pollution reduction, access to green spaces, and flood-depth reduction. Then, the results are normalized to construct a scale that permits the comparison among the different dimensions of the benefits. For the analysis of the economic benefits from the reduction in damages to physical assets form flooding waters, the flood footprint uses the results from the flood-depth reduction provided by the MBT.

The MBT was basically constructed to conceptually show that it is possible to assess the multiple benefits of diverse strategies for sustainable urban drainage systems (SUDS). The BGI would consider as part of a SUDS. The toolbox has been built to consider the spatial and context circumstances of each of the BGI features.

The evaluation of the multiple benefits within the MBT is based on the following three principles:

1. Normalization: it provides a common scale that makes possible the comparison among different benefits as the reduction in flood damage and reduction of noise.
2. Spatial: As the tool is based on a GIS, it is possible to identify the benefit with high accuracy and show the distribution of the benefits.
3. Context sensitive: the tool also considers the specific features located in each context, so that the same interventions of a certain SUDS would have different results in different locations.

The process that the MBT follows for the evaluation of the multiple benefits is divided into three different stages: First, the characteristic model; second, a single benefit evaluation is carried out; and finally, the evaluation of the multiple benefits is done.

Characteristic modelling incorporates the specific benefit data to create a raster and present the geographical distribution of a characteristic of interest. For instance, the model considers a specific unit in which each of the benefits can be measured, e.g. the depth in centimetres in each squared metre of flooding water. This analysis is carried out twice, first under the reference scenario and secondly under the scenario case, to evaluate the difference of the intervention in terms of the appropriate units of each characteristic. This provides, in the specific unit, the benefits of the intervention.

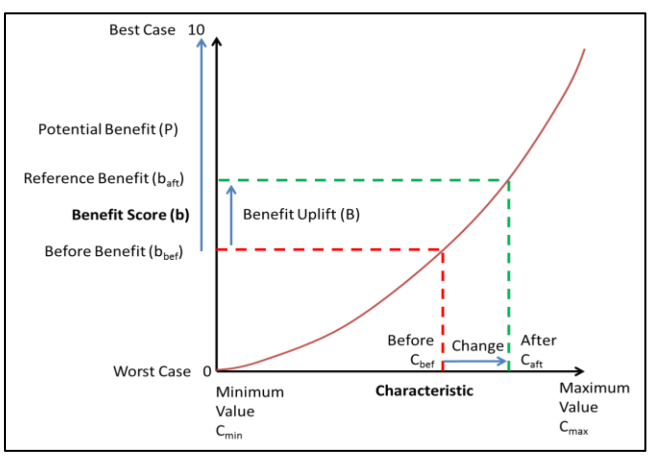
The single benefit evaluation normalises the results from the characteristic modelling into a scale 0-10 to be able to compare with the benefits of other characteristics. The normalisation is based on each specific characteristic and an equation of normalisation is developed in each case.

The final stage considers the evaluation of the multiple benefits based on the normalised values of each case. The results are weighed or unweighted to determine the total benefits in each location. The multiple benefits are scaled within -10 and +10 values, where -10 represent the transition, from the reference scenario, to the worst possible case. On the other hand, the value +10 represent the transition, from the reference case, to the best possible case.

The results of the multiple benefits evaluation are geographically distributed to consider the location where best of worst scenarios take place. This provides with a picture about where the best potential benefits would be obtained with the scenario case, in comparison with the reference case. When the results are negative, it shows where the intervention would present disadvantages when compared with the reference scenario. In this case, the reference scenario would refer to the GI case, while the intervention would be represented by the BGI scenario.

After obtaining the evaluation of the multiple benefits, the MBT uses a graphical tool (*the benefit curve*) for the interpretation of the changes in a characteristic in relation to the overall benefit score (see **Figure 7.1**).

Figure 7.1 Benefit Curve showing the derivation of Benefit score and potential benefit



Source: Morgan and Fenner (2017).

The MBT can display the results in an intensity raster map, which shows the geographical distribution of different levels of benefit in the locations of treatment and surrounding areas.

The last stage of the MBT assessment considers a measure of effectiveness of the SUDS scenario (BGI in this case). The measure considers the ration of the Benefit Score against the Potential Benefit within a scale 0 to 1. This provides with a measure about the effectiveness of the treatment scenario in each location.

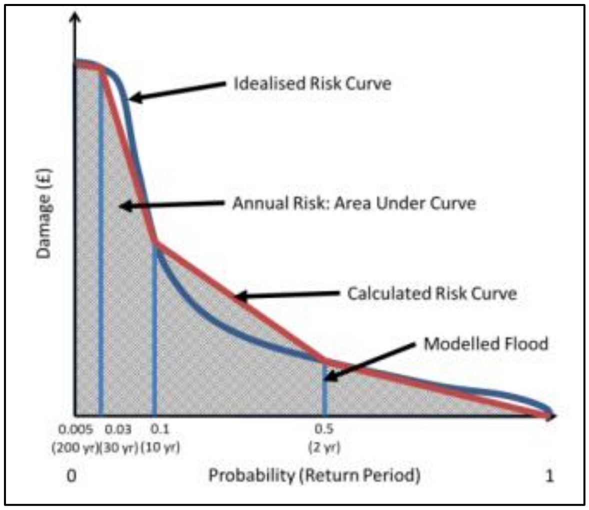
For the assessment of multiple benefits from BGI (as a strategy in the development of a SUDS), the MBT evaluates the benefits of 6 different aspects that may represent benefits after BGI is in place: access to green space, air pollution quality, carbon sequestration, greenspace or water habitat size, noise, and flooding depth.

Is the last characteristic, the evaluation flooding depth under reference scenario (GI) and case scenario (BGI), which provides the information to incorporate it later into the flood footprint analysis.

For the evaluation of the flooding depth and the costs related with the damages from flooding waters, the MBT incorporate, first, the information from a flood model that provides the water depth in each location. Secondly, it combines the information with a map of land use categories and built infrastructure, such that the depth of water in each asset is approximated. The land use categories available in the maps includes residential high density, residential low density, commercial, industrial, mines/construction, recreation, nature, and water. Some categories in the built infrastructure maps includes roads, railways, restaurants, banks, hotels, schools, residential, etc.

Once water depth in each asset is approximated, the MBT incorporates a series of damage functions (by each land use category) to assess the cost of the physical damages from flooding water, under both reference scenario and treatment scenario. The damage functions provide with a functional relation between the flood depth and the costs related to the infrastructure in each of the land use categories. The damage from each return period is then used to calculate the annual risk of damage (see Figure 7.2).

Figure 7.2 Example damage probability curve



Source: Blue Green Cities Research Project (2016)

7.2.2 Nexus between the MBT and the flood footprint models

The hybrid approach to assess the potential economic benefits of BGI, derived from flood damage mitigation, consists of three stages. First, the MBT calculates the economic damage of a specific return period event under both BGI and GI scenarios, for a specific urban area. This provides the direct damages by land use category. Secondly, the results from the MBT are encoded to match with the industrial categories in the flood footprint model. This is based on a weighted distribution of the economic activity and the size of the city's economy. Finally, the flood footprint model is regionalised for the targeted economy, and it incorporates the data of the direct damages under each of the infrastructure scenarios. The potential direct and indirect benefits for a given return period event are then considered as the difference of the flood footprint estimations under both infrastructure scenarios.

The model provides the results by each category of direct and indirect benefits. The disaggregation of benefits by economic sectors are also determined by this approach.

7.3 Data gathering and codification

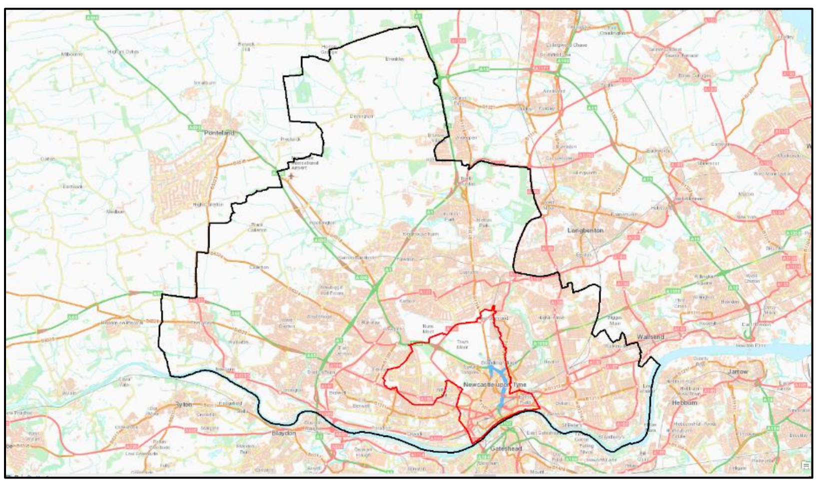
The assessment of the BGI benefit focusses on the City of Newcastle, and the experiment considers six return period scenarios: 200, 100, 50, 30, 10, and 2 years. The return period refers to the probability that an event of a specific magnitude occurs in that period of time. For instance, a return period of 200 years could be seen as an event with an occurrence's probability of 1/200 or 0.5 % in a year. As bigger the return period, the more intense the event and the lower the probability of occurrence within a given year.

For the MBT, we only describe the data needed for the assessment of flood damages, leaving aside the rest of the benefits dimensions that the tool is able to assess. For that purpose, three sets of data are needed: hazard information, infrastructure in place, and damage functions.

7.3.1 Hazard information

The hazard information includes the spatial distribution of flood depth under both GI and BGI scenarios. This data was taken from the City Catchment Analysis Tool (CityCAT), a hydrodynamic model that is able to assess the effects of BG features on water flows and flood depths (Glenis, Kilsby, Kutija, & Quinn, 2010). The model ran over the urban core area marked with red in the Figure 7.3, which includes parts of the wards of Wingrove, Westgate, Ousborne, South Jesmond, North Jesmond.

Figure 7.3 Newcastle Upon Tyne. Urban core (in red) and the City's administrative boundary (in black)



Source: Blue Green Cities Research Project (2016)

7.3.2 Infrastructure information

The information for the urban infrastructure is gathered using the land use distribution and building-type information. The mapping of land use categories are provided in an Ordnance Survey (OS) MasterMap Topographical Layer[34], while building type information is from the OS Gazetteer Database, supplied by Newcastle City Council (Blue Green Cities Research Project, 2016). MasterMap identifies eight land use categories: Residential High Density, Residential

[34] https://www.ordnancesurvey.co.uk/business-and-government/products/topography-layer.html

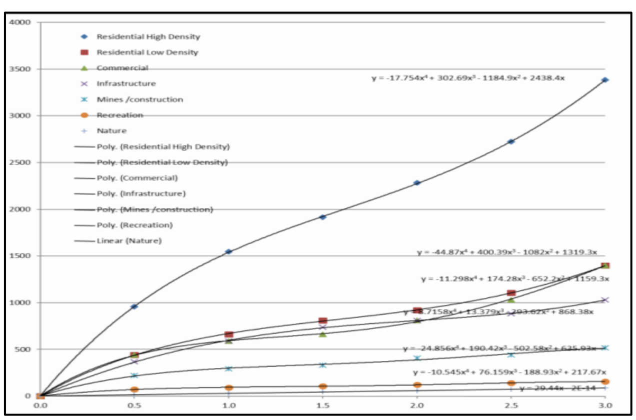
Low Density, Commercial, Industrial, Mines/Construction, Recreation, Nature, Water. On its part, 104 building type categories are identified in the Gazatteer database, e.g. road, building commercial offices, building residential dwelling terrace, railway.

To create the BGI scenario, a hypothetical selection of BGI was added to areas in the city. In Wingrove, a residential area to the north-west of the urban core, all gardens were designated as greenspace, additional greenspace was added to public areas (equivalent to raingardens) and all pavements and back alleys were designated as permeable paving. Hypothetical BGI interventions were also added around Newcastle University (permeable paving and green roofs) and along streets in the urban core. These include: Northumberland Street and John Dobson Streets (green roofs, small (2x2m) swales, permeable paving and street trees), and St James' Boulevard (a large swale along the length of the road and permeable paving) (Blue Green Cities Research Project, 2016; Morgan & Fenner, in press). The flood inundation damages were then calculated using the MBT for the reference case (no additional BGI) and BGI scenario. The flood depth for each building and other types of urban infrastructure were assigned and linked to a land use category.

7.3.3 Damage functions

Finally, damage functions were used to calculate a monetary value of the flood damage for the different return periods. These damage functions integrate information on flood depth, type of building, and land use (see Figure 7.4). Each land use has its own depth damage curve which range from £88/m^2 for Nature to £3385/m^2 for Residential High Density category for a 3m deep flood (the maximum depth considered) (Morgan & Fenner, in press).

Figure 7.4 Depth damage curves used in the MBT



Source: Blue Green Cities Research Project (2016).

This information constitutes the basis for constructing the EAM for the flood footprint model, although it has to be encoded first to match the categories of economic sectors in the flood footprint model. The flood footprint model requires two sets of data: economic data about the affected region and information about the disaster. A monthly time scale is used for the temporal analysis, and the sectoral disaggregation uses 46 economic sectors.

7.3.4 Economic data for flood footprint model

The economic data include information on capital stock, final demand, employment, and inter-industrial transactions. All the information has been either collected or regionalised at the city level, and when monetary, the values are in millions of pounds (£million) at 2009 prices.

Capital stock data are only available at the national level. The regionalisation consisted of obtaining the productivity of each sector at the national level and then adjusting by city's output, assuming the same productivity as the national average. The regional dwelling capital is the proportion of housing in the region multiplied by the national dwelling capital. For the city of Newcastle, this accounts for 0.54%.

The categories for final demand (households, government, capital, imports and exports) were obtained from the UK-Multisectoral Dynamic Model (MDM), by Cambridge Econometrics Ltd[35]. This is a macro-econometric model used to analyse and forecast environmental, energy and economic data for twelve regions in the UK. The model provides the data for the North East region and for 46 industrial sectors.

To regionalise the data at city scale we used the employment data, which gives details at the city scale for 18 economic activities. These data were obtained from the 2011 Census by the Office of National Statistics (ONS)[36]. To match the sectoral disaggregation with 46 sectors in the MDM with the rest of the data, a weighted distribution was followed based on both national employment and the value-added data from the MDM.

For inter-industrial transactions data, a regionalised matrix of technical coefficients had to be derived from the national IO tables owing to the lack of regional tables. For this purpose, we follow a standard statistical technique in IO modelling, the Augmented Flegg Location Quotients

[35] http://www.camecon.com/how/mdm-e3-model/

[36] https://www.ons.gov.uk/employmentandlabourmarket/peoplenotinwork/economicinactivity/adhocs/005609ct05822011censuseconomicactivity

(AFLQ) to obtain the regional IO coefficients matrix for the city of Newcastle upon Tyne. This technique seeks to correct the national technical coefficients to depict regional technology, given the regional economic structure (Flegg & Webber, 2000; Miller & Blair, 2009; C. A. Romero et al., 2012). The transactions' values are obtained later by multiplying the regionalised matrix of technical coefficients by the regional output.

7.3.5 Disaster Data

This data is given by the MBT as the monetary value of damages, based on flood depth, by building type. The data is then allocated to either residential damage or to an economic sector to determine the damage to industrial capital. The proportions of damages to industrial capital are then disclosed in the diagonal elements of the EAM.

Labour constraints were modelled as a proportion of the number of flooded houses multiplied by the average number of working people per household. Additionally, commuting delays were proportionally related to damage in the transport sectors. A sensitivity analysis was also carried out on this parameter to assure robust results.

7.4 Results

The results of the MBT analysis shows that one of the advantages of BGI is the reduction of water depth in all flooding scenarios and in consequence, the associated direct damages. This implies that BGI brings potential economic benefits (or avoided damages) in flood risk management. The results are shown in this section.

The calculations show that direct and indirect damages are both lower under BGI scenarios when compared with GI scenarios. The difference of damages between GI and BGI scenarios represents the economic benefits (or the avoided costs) of BGI, for each return period event.

7.4.1 Flood Footprint

Table 7.1 Flood Footprint for Grey (G) and BG infrastructure (£million)

Scenario	Direct Residential	Direct Industrial	Indirect Damage	Total FF
G_R2	44.19	134.54	19.13	**197.87**
G_R10	63.24	218.98	64.82	**347.04**
G_R30	78.30	294.90	121.15	**494.35**
G_R50	85.81	336.33	176.57	**598.71**
G_R100	96.90	399.83	358.34	**855.08**
G_R200	109.76	473.10	1,363.43	**1946.29**
BG_R2	31.54	118.70	14.41	**164.64**
BG_R10	53.21	201.00	32.98	**287.19**
BG_R30	70.44	276.08	60.21	**406.73**
BG_R50	78.83	317.65	101.54	**498.01**
BG_R100	91.08	381.19	200.50	**672.77**
BG_R200	104.60	454.51	826.25	**1385.36**

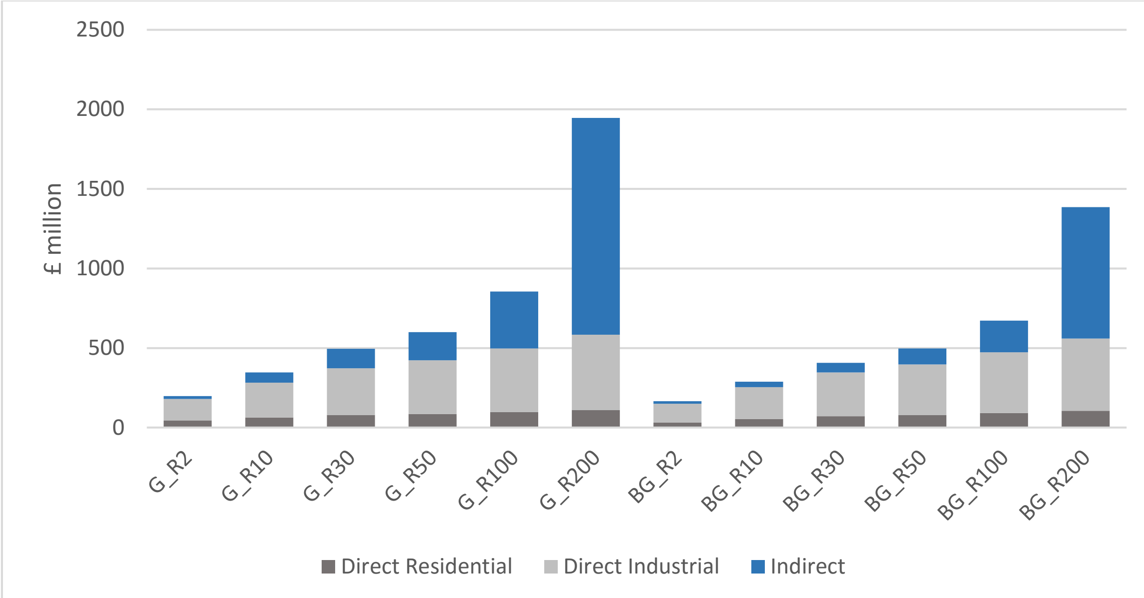
All values are in £million

G_R[x] is Grey infrastructure scenario for x years return period

G_R[x] is Blue Green Infrastructure scenario for x years return period

The Table 7.1 Flood Footprint for Grey (G) and BG infrastructure (£million) shows the results of the flood footprint analysis for each of the return periods and for both GI and BGI scenarios. The results are disclosed by the components of damage, i.e. the direct damages integrated by damages to both residential and industrial capital, and the indirect damages. All damages for the same return period are bigger within the GI scenario than within the BGI scenario. This indicates that the BGI provides a reduction of direct and indirect damages for all return period events.

Figure 7.5 Flood Footprint for Grey Infrastructure & Blue Green Infrastructure for all return periods



In Figure 7.5 the proportions of direct (in grey) and indirect (in blue) damages for the 12 scenarios are illustrated, where G = Grey Infrastructure and BG = Blue-Green Infrastructure.

In both infrastructure scenarios. This is a graphical representation of the results in Table 7.1, showing the shares of residential and industrial direct damages, and indirect damages. The indirect damages increase more than proportionally as the intensity of the flood increases. Consequently, the indirect damages do it as well. It is also remarkable that the indirect damages are relatively insignificant for events with a short return period. However, it is in the 200 years return period event where the indirect damages become the major share of damages within the flood footprint.

It is notorious that the residential damages represent in all cases a small proportion, which remains relatively constant, around the 20% of the direct damages.

Regarding indirect damages, they account for a share that goes from the 10% to the 70% in under GI scenarios, while the proportion of indirect damages for the BGI scenarios runs from 9% to 60%. This indicates that BGI not only helps in reducing the direct damages from a flooding event. The indirect damages, as proportion of total flood footprint, is also reduced.

Finally, the total flood footprint under GI scenario goes from the £200 million (for the 2 years return period event) to nearly £2,000 million (for the 200 years return period event). On the other hand, the value of flood footprint under BGI goes from £164 million (for the 2 years return period event), to £1,400 million (for the 200 years return period event). This represents a reduction in cost under BGI, which goes from the £36 million (for the 2 years return period event) to nearly £600 million (for the 200 years return period event).

7.4.2 BGI benefits

As mentioned before, the benefits of BGI are considered as the reduction in total damages under BGI infrastructure scenario, regarding the current situation of GI. This is, for each return period event, the difference of damages in the grey part of Table 7.1 (G_R scenarios), minus the result of the blue part from the same table (the BG_R scenarios).

The estimations of direct damages from the MBT shows a decrease (in relative terms) of difference between GI scenarios and the BGI scenarios, for all return period events. This difference goes from 30% of damages reduction between GI and BGI scenarios for the 2 years return period, to a difference of just 5% between GI and BGI scenarios for the 200 years return period. However, the story is different for the indirect damages. The percentage change of differences of indirect damages between GI and BGI scenarios increases from 25% in the 2 years return period event, to reach a peak of 50% in the 30 years return period event. Then the proportion of the differences decreases until 39% for the 200 years return period event. However, the proportional differences are always bigger for indirect damages than for direct damages.

Figure 7.6 BGI benefits (avoided direct and indirect costs)

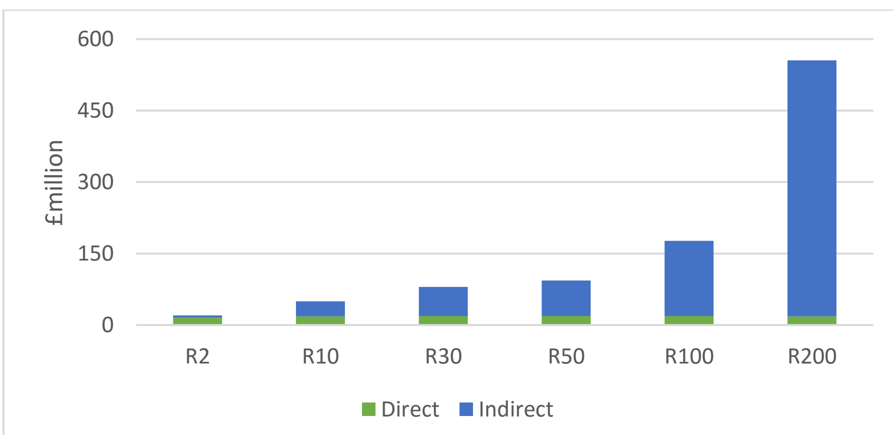


Figure 7.6 shows the total benefits (or avoided costs) for the BGI scenario, regarding the GI scenario. The direct ‘benefits’, or the avoided direct damages, remain relatively constant for all return periods (in absolute terms), accounting for around £25 million. The story is different for the indirect damages ‘benefits’, or avoided indirect damages, as they experience a huge increase from £5 million in the 2 years return period, up to £537 million for the 200 years return

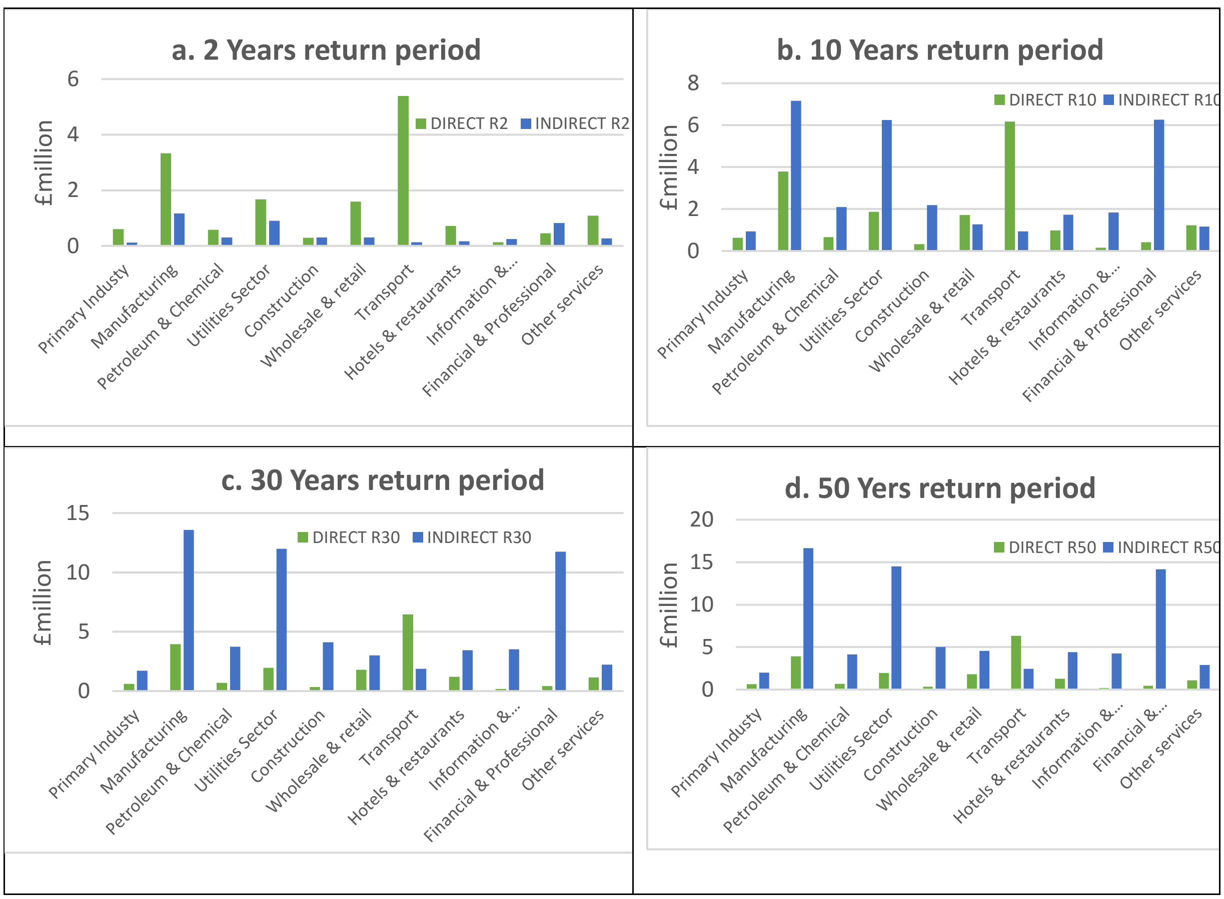
period. In relative terms, the share of indirect benefits goes from 14% of total benefits (for the 2 years return period), up to the 96% of total benefits (for the 200 years return period). Even if these results are biased for the data generated by the MBT, they reinforce the idea that indirect damages will contribute more to the flood footprint as the intensity of the flood increases, affecting critical infrastructure and consequently triggering major disruptions in the economy.

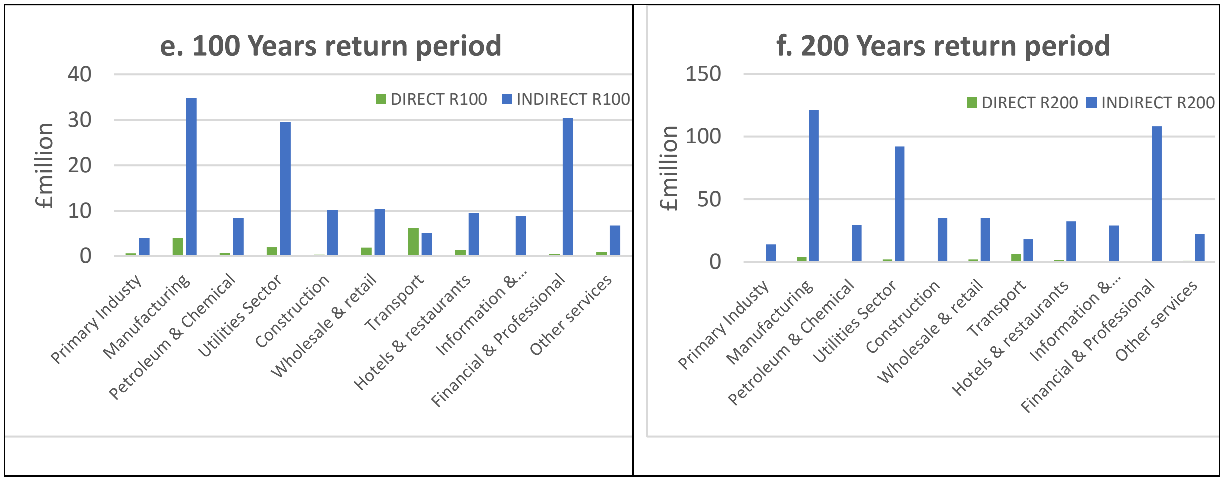
7.4.3 Sectoral distribution of benefits

This subsection presents the distribution of benefits by economic sectors.

Figure 7.7 (a-f) depicts the distribution of the benefits by industry, for each of the return period. It can be noted that the sectoral distribution is very similar among the different scenarios for each category (indirect and direct benefits), as this depends mostly on the economic structure, which does not change over the different return period events. The different scale for each of the charts should be noted.

Figure 7.7 BGI benefits by industry





The direct benefits concentrate more in those sectors that would be directly benefited from a reduction in the flood waters. This occurs more in those sectors that have a bigger proportion of built infrastructure as part of the capital stock, as it is the case of Manufacturing, Utilities, and Transport sectors. In the case of the indirect 'benefits', they concentrate gain in Manufacturing and Utilities sectors. Other industries highly benefited indirectly from the avoided damages are those enclosed in the Financial & Professional sectors. This result has been found in other case studies, as these sectors are highly dependent on the functioning of those sectors related with infrastructure, such as Transport and Utilities sectors.

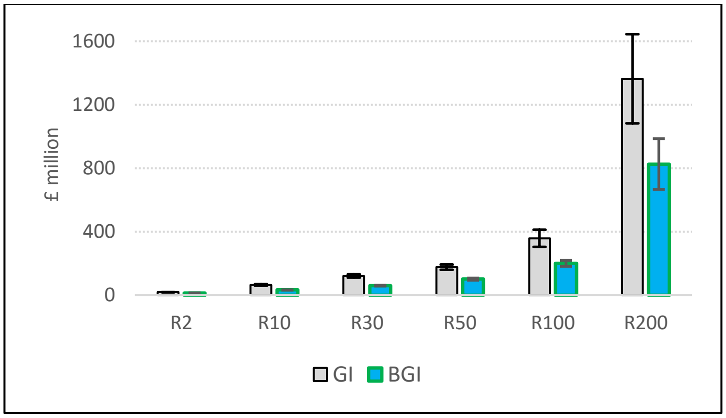
The sectoral analysis depicts the potential damages to specific industries, and highlights the hot spots where more attention should be put to increase the benefits of BGI.

7.4.4 Sensitivity Analysis

A sensitivity analysis was carried out on the model parameters related with the damage curve for labour, and behavioural changes in final demand. As parameters only affect the appraisal of indirect damages, this is the category upon which the sensitivity analysis is done. The sensitivity analysis comprises the upwards and downwards variation of 30% of the parameters in intervals of 5%.

Related to final demand, the variation of parameters comprises the decreased proportion of consumption in non-basic products. While for labour, the variation of parameters comprises the proportion of labour not available for traveling, and the proportion and time of labour delayed by transport constraints. Here are presented the results of a global sensitivity analysis, this is, the results of variations in all parameters at the time. This is due to changes in final demand parameters gave non-significant changes in results.

Figure 7.8 Sensitivity analysis by return period



The error bars in Figure 7.8 show the standard error of indirect damages by return period. The standard errors for the different return periods range from 4.3% to 20% under GI scenario. Likewise, these values range from 3% to 19% under BGI scenario. When considering the differences between both scenarios (or the indirect benefits), the values range from 7.7% to 22.5% (see Figure 7.9)

Figure 7.9 Sensitivity analysis for indirect benefits

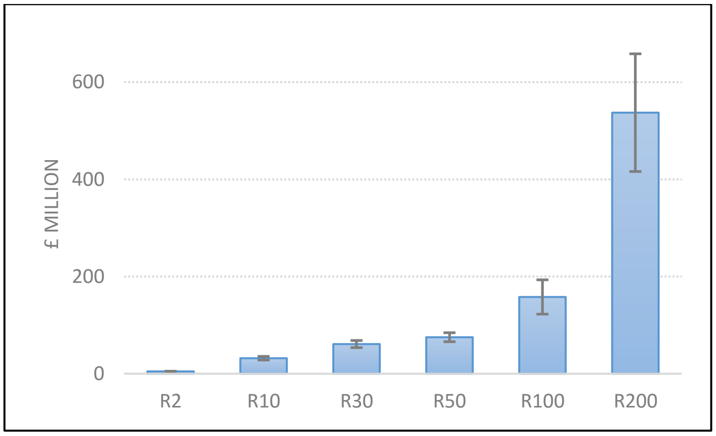
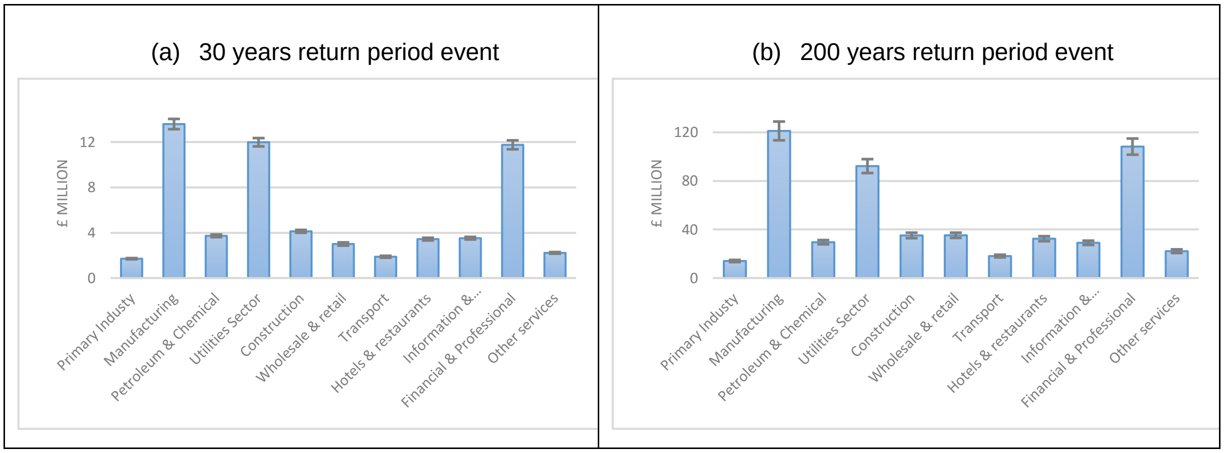


Figure 7.9 presents the standard error of indirect benefits by groups of industry sectors, for 30 years (a) and 200 years (b) return periods. The maximum errors, in relative terms, are found in Manufacturing sector, with a variation of 3.3% and 6.3% regarding the mean value of the respective return period. Likewise, the minimum errors are found in Primary Industry sector, which represents a deviation of 2.4% and 6% from the mean value of the respective return period.

Figure 7.10 Sensitivity analysis by industry group



The sensitivity analysis shows that the model is relatively stable, and the results can be considered robust, as variations in the model parameters causes less than proportional changes in results. In this case, a maximum variation of ± 30% in the parameters values results in a cumulative standard error equivalent to 22% of the mean value of the total indirect damages of the 200-years return period event.

7.5 Summary

This chapter presented a hybrid and novel methodology to assess the total economic benefits of a given flood risk management option. The novelty of the approach rests in a consistent integration of flood inundation modelling with the Multiple Benefits GIS toolbox, which links and encodes the results from flood inundation modelling into economic information for impact assessments. Finally, the flood footprint assessment framework was applied to consider all the interlinked economic transactions within a city scale to assess the indirect damages to a regional economy from different flooding events. The flood footprint method incorporates the modelling of important elements in the aftermath of a flood event for a wider understanding of the economic consequences of flooding and the recovery process, such as disruptions in labour and shortages in the supply chain.

This allows to evaluate the total avoided costs (which here we defined as economic benefits) of implementing BGI as a flood risk management strategy.

The method presented here contributes in research into flood risk management and adaptation strategies to climate change in urban areas, and provides a consistent assessment tool to determine the potential benefits of a flood risk management strategy.

The data presented here show that incorporation of BGI is a viable option to help mitigate damages related to flood risk, potential climate change, and weather-related disasters within a city’s environment.

This approach confirms the potential benefits of BGI, not just confined to the area where the assets are build, but to wider economic networks. The results show that indirect benefits may be strongly allocated to sectors that are not directly protected by BGI but depend on the appropriate functioning of other sectors under flooding and aftermath circumstances.

Overall, the results provide evidence that benefits from a strategy for flood risk management may bring additional benefits to consider in cost-benefit analysis to evaluate the viability of a certain strategy, and an ad hoc methodology to assess those potential indirect benefits.

Chapter 8 Conclusions

Based on the overarching aim, this concluding chapter summarises the contributions and limitations of this thesis, and provides suggestions for future research.

8.1 Contribution to knowledge

The overarching aim of this thesis has been to develop a useful methodology to assess the economic costs from physical damages arising from a climate extreme event to understand how an economic shock from a climatic extreme event is transmitted and propagated to wider economic systems and social networks generating additional indirect economic costs.

This thesis presented the development of an impact assessment model based on the IO economic framework. The final model is capable of accounting for the diversity of economic consequences that arise after the economic shock imposed by a natural disaster. The goal was twofold as it is the intention to estimate, firstly, the direct damage to each economic sector or industry based on the information provided by different estimation methods to quantify flooding damages to physical assets, such as financial reports or depth damage functions and flood modelling. Secondly and most challenging, is the estimation of secondary effects, considering the economic mechanisms, that affects the production in the sectors and regions that are economically linked with the affected region.

8.2 Key method development

Moreover, the methodology, at each stage in its development, was tested and its usefulness demonstrated when applied to each case study, whose results were of great relevance for the impact analysis embodied in each of the projects where it was applied.

The final version of the flood footprint model, developed during the course of this thesis, is a model that considers the flooding damages to physical assets including infrastructure, industrial capital and residential capital. It also accounts for the disruptions to the labour force that is also experienced during a climate extreme event. Moreover, the model is also able to incorporate behavioural changes in final consumption.

Therefore, the model evaluates the production disruptions to inter-linked economic sectors, both within and outside the flooded region. From this point of view, the model provides a dynamic recovery route-map that the economy can follow towards its recovery. In summary, it provides a general picture of the total multi-regional economic effects resulting from a climate extreme event.

The methodology offers novelty in three main ways:

• Extension: it incorporates methodological elements to consider diverse aspects of economic impact analysis that had not been previously incorporated in an integrated model. These comprises the multiregional dimension of the analysis, the dynamic-time recovery, the effects from labour disruptions and residential damages, the behavioural change on final consumption, and the transition from capital investment for recovery to reconstruction of productive capacity.

The process of the model's development can clearly be divided into three stages, which are linked to the corresponding case studies:

- Single-regional flood footprint: The first stage is related to the calibration of the parameters and functionality of the ARIO model in a past real event.
- Multiple single-regional flood footprint analysis: This represents an intermediary step between the single-regional model and the multi-regional model. An important development is the incorporation of the concept of capital matrix into the recovery process. This provides theoretical consistency to the methodology, in the transition of changes from a stock variable to a flow variable.
- Multi-regional flood footprint analysis: This stage presents the final improvement to the flood footprint analytical framework, and refines the modelling of labour damage function at this stage.

• Applicability: Parallel to each stage of the model development was a related case study, which were chosen based on the relevance of the event or the scenario to which they refer:

The single-regional model was applied to the analysis of the 2007 summer floods in the UK. The analysis if for the regions of Yorkshire and the Humber, which were the most affected by the event. This application was based upon a past real event.

The multiple single-regional analysis was applied to the 2009 summer floods in Central Europe and the 2010 Xynthia windstorm. The case was once more applied to real past events that, in this case, affected a several subnational regions across different countries.

The multiregional analysis was applied to a hypothetical case considering future scenarios of climate change and socioeconomic development in the city of Rotterdam, The Netherlands.

- Adaptability: We distinguish two main directions in which the flood footprint can adapt, given the experiences of the case studies.

First, the possibility of integration of the flood footprint and economic model with models from other disciplines, such as engineering flood models, GIS models, depth damage functions, or more traditional reports from damage evaluation *in situ*. This expands the potential of flood footprint modelling, as flood modelling has experienced rapid development in recent years. Additionally, GIS models can make more accurate estimations of the geographical distribution of damages, and in combination with depth damage functions provide a more accurate and efficient estimation of the damages.

Secondly, the flood footprint framework has been shown to adapt to other purposes. In this thesis, the transferability of the model was demonstrated when applied to other natural hazards in addition to flooding events, as shown in the case of the 2010 Xynthia windstorm. Moreover, the model was applied to assess the benefits of a flood risk management strategy. This is the case study of the evaluation of blue-green infrastructure in the city of Newcastle upon Tyne, UK as an option to mitigate the damage caused by flooding events.

8.3 Summary of key findings and policy implications

Table 8.1presents a summary of the results from the case studies. It is not the intention to suggest a comparative analysis as each case presents very different characteristics, such as the different regional and economic contexts, the nature of the climate extreme events and the consequences to each particular environment.

Table 8.1 Summary of results of case studies

Region	FF	Indirect/FF (%)	Annual GVA	FF/GVA (%)	Currency
Yorkshire and The Humber	2,700	55.55	69,000	3.91	(£ million 2007)
Central Europe	1,019	65.03	787,867	0.13	(€ million 2007)
Western and South Europe	9,000	50.89	5,390,508	0.17	(€ million 2007)
Rotterdam	11,998	39.02	117,500	10.21	(€ million 2007)
Newcastle Grey	198 – 1,946	9.90 – 69.96	25,448	0.77 - 7.65	(£ million 2009)
Newcastle Blue-Green	165 – 1,385	9.09 – 59.67	25,448	0.65 - 5.44	(£ million 2009)

However, some general insights can be drawn from the results of these case studies.

First, the proportion of indirect damage over the total economic costs of a climate extreme event (or flood footprint) represents a considerable share that ranges from 9.09% to 69.96%. This fact by itself justifies the relevance of accounting for the indirect damages of a climate extreme event, or from an economic shock in general. The risk of not considering the indirect effects can undermine flood risk management strategy, leaving exposed to further damages those sectors that are indirectly affected.

Secondly, it is notable that direct damages are concentrated in the manufacturing and infrastructure service sectors, such as electricity, gas and water, telecommunications, and transport. Whereas the indirect costs tend to accumulate in the tertiary sectors, such as the financial and other businesses sectors. This can be explained by two factors. On the one hand, the manufacturing sectors and infrastructure sectors have, in general, more in-built capital stock and equipment so that more capital is exposed to damage from floodwater. On the other hand, business services and other related sectors rely largely on infrastructure services, such as the transport and telecom sectors. A small failure in the infrastructure sectors would imply severe production disruptions in the business sectors.

The flood footprint analysis also explores how sensitive the level of damages is to changes in the labour constraint parameters. While it may be true that information on labour constraints is still very limited and strong assumptions are to be accepted, the analysis showed that the production in industrialized economies are highly capital intensive, so that the productivity of labour is consequently high. Specifically, the value-added generated by each employee in an industrialised economy is, on average, higher than in the less industrialised countries. The consequences are that the risk of flood damages is higher when the workforce is exposed to severe disruptions.

Finally, the multi-regional flood footprint analysis reveals the interconnected of modern economies, such that a shock affecting a regional economy will have consequences in its commercial partners. This last point raises the necessity to create regional adaptation strategies to reduce the risk of climate change, as the consequences of these changes extends across all economies linked, directly or indirectly, to the affected region.

8.4 Implications for stakeholders and policy makers

The flood footprint analysis identifies the worst affected sectors by both direct and indirect damages, after a climate extreme event. For investment in risk management options for natural disasters, it is critical to identify the 'blind-spots' in critical infrastructure and vulnerable sectors along with the economic supply chains and social networks. This in turn allows for sufficient adaptation to the damage that is transferred from the current event to future events. Adaptation to natural disaster risk is not limited to the area suffering direct damage. It also extends to its socio-economic networks and this must be considered in order to minimise the magnitude and probability of cascading damage to other regions.

At the level of disaster risk mitigation responsibility, the flood footprint analysis would provide an alternative way to allocate financial responsibility for disaster risk mitigation interventions by incorporating the value of all stakeholders' economic capacities on the local/regional/national/international supply chains, based on the 'who benefits, who pays' principle. In other words, if a disaster footprint assessment reveals that organisation(s) x or y benefit in a large way from natural disaster defence then alternative management payment schemes could be looked at. This could potentially reduce the government's financial burden for risk management of natural disasters, and spread the cost between major stakeholders in the supply chain, based on the 'who benefits, who pays' principle.

In the international context of climate change, a flood footprint analysis could potentially reduce the financial burden and reallocate resources for climate risk management in more vulnerable regions of the world, spreading the cost between major economies in the supply chain that would potentially benefit from climate risk reduction in those more vulnerable regions.

At a communication level, the flood footprint could be an excellent concept to enhance business and public awareness of the possible damage threatening them as well as the total damage a flood can cause.

8.5 Limitations of the study

The main limitation of the flood footprint modelling comes from the dataset.

Flood modelling is greatly improving and is able to deliver very accurate estimations of floodwater depth, however when translating the flooding characteristics into economic damages, the use of depth flood damages uses average damage values for a generic asset. This creates a degree of uncertainty and bias in the analysis.

The data available on labour and household consumption in the aftermath of a flood are very limited. The former represents a serious source of uncertainty, as the model presents high sensitivity to small changes in labour parameters, while variations in the latter do not affect the results considerably.

The multi-regional analysis is also limited to a national-level analysis, as multi-regional tables at the sub-national level exist for very few countries.

Other limitations are related to the nature of the subjacent IO model, such as rigidities for inputs substitutions, and fixed-proportions production functions.

Another limitation in the model is that the recovery does not consider the economic growing path, as the recovery is considered when the economy reaches the pre-disaster conditions.

8.6 Future research

The usefulness of the flood footprint developed here has been demonstrated in four case studies. These cases allowed for application of the model outside of the academic arena, where other researchers, policy makers and stakeholders can be provided with valuable feedback for improvements and developments to the model. In general, the flood footprint has delivered robust and useful results. However, some aspects deserve attention to improve and expand the potential capability of the methodology.

First, the computing capabilities and advances in science understanding of the effects of climate change can provide an estimation of a climate extreme event almost in real time, as soon as some parameters of the extreme climate event are known. A ‘climate risk map’ could be developed to reduce the vulnerability and enhance the resilience of the regions and sectors at risk. It is a future plan to develop, within the flood footprint model, an *ad hoc* module that incorporates information from flooding maps, in-built infrastructure, economic activity of the in-built assets, and depth damage functions, and processes it using GIS techniques (or any other appropriated technique) to provide an estimation of direct damages. This would provide a consistent analysis across different cases and would significantly reduce analysis time.

Second, as the frequency of climate extreme events increases, some regions are impacted by a second natural hazard before the economy is fully recovered from the previous one. It is intended to extend the flood footprint to assess these types of scenarios by incorporating adaptation measures that may reduce the impact of subsequent disasters. This situation suggests another development of the model, which is the incorporation and assessment of adaptation strategies, for example using blue-green infrastructure.

Third, as the case studies show that impacted economies take over a year to recover after a major flooding event, it has been pointed out that the production would have grown in the absence of the climate extreme event, so that the recovery of the economy should aim to reach this projected level of production.

Furthermore, to cope with the uncertainties presented in the analysis, a systematic sensitivity analysis should be incorporated into the modelling. While a sensitivity analysis was conducted for the case studies presented in this thesis, the methodology needs refinement in order to apply it systematically and to be incorporated as a standard part of the modelling process.

Finally, further research should aim to map the climatic risk along the global value chain. In climate change economics, the mitigation of climate change is usually seen as a global problem, while adaptation is relegated as a local problem. The evidence provided by an alike analysis as the multi-regional flood footprint would point out the need to develop global adaptation strategies, such as allocating resources for climate risk management in those vulnerable regions that, if impacted by a natural hazard, would trigger severe indirect damages to other countries with more resources for adaptation. Therefore, the analysis could be applied to provide evidence that may raise awareness for the need of a global adaptation strategy.

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Appendix. Mendoza-Tinoco, D., Guan, D., Zeng, Z., Xia, Y., Serrano, A. (2017) Flood footprint of the 2007 floods in the UK: The case of the Yorkshire and The Humber region, in Journal of Cleaner Production 168 pp. 655-667 https://doi.org/10.1016/j.jclepro.2017.09.016

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Flood footprint of the 2007 floods in the UK: The case of the Yorkshire and The Humber region

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ABSTRACT

International headlines over the last few years have been dominated by extreme weather events, and floods have been amongst the most frequent and devastating. These disasters represent high costs and functional disruptions to societies and economies. The consequent breakdown of the economic equilibrium exacerbates the losses of the initial physical damages and generates indirect costs that largely amplify the burden of the total damage. Neglecting indirect damages results in misleading results regarding the real dimensions of the costs and prevents accurate decision-making in flood risk management. To obtain an accurate assessment of total flooding costs, this paper introduces the *flood footprint* concept, as a novel accounting framework that measures the total economic impact that is directly and indirectly caused to the productive system, triggered by the flooding damages to the productive factors, infrastructure and residential capital. The assessment framework account for the damages in the flooded region as well as in wider economic systems and social networks. The flood footprint builds on previous research on disaster impact analysis based on Input-Output methodology, which considers inter-industry flows of goods and services for economic output. The framework was applied to the 2007 summer floods in the UK to determine the total economic impact in the region of Yorkshire and The Humber. The results suggest that the total economic burden of the floods was approximately 4% of the region's GVA (£2.7 billion), from which over half comes from knock-on effects during the 14 months that the economy of Yorkshire and The Humber last to recover. This paper is the first to apply the conceptual framework of *flood footprint* to a real past event, by which it highlights the economic interdependence among industrial sectors. Through such interrelationships, the economic impacts of a flooding event spill over into the entire economic system, and some of the most affected sectors can be those that are not directly damaged. Neglecting the impact of indirect damages would underestimate the total social costs of flooding events, and mislead the correspondent actions for risk management and adaptation.

1. Introduction

In recent decades, the frequency and intensity of climate-related natural hazards have both increased. Extreme flooding and flood-related events are leading this trend, and the United Kingdom has been particularly affected by these phenomena (Committee of Climate Change, 2016).

These events have resulted in severe social and economic costs all over the world. Damages to labour and capital productivity after a disaster create knock-on effects that exacerbate the initial losses of the flooded assets, disturbing not only the impacted economic sectors but also other sectors that are indirectly affected through economic mechanisms. This sequence of events can be observed in the 2007 summer floods that occurred in England, which caused a major civil emergency nationwide. Thirteen people were killed and approximately 7000 had to be rescued from flooded areas; 55,000 properties were flooded and over half a million people experienced shortages of water and electricity (Pitt, 2008). The most affected region was Yorkshire and the Humber (Y&H) which accounted for

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Source: Wikimedia Commons.[1]

Fig. 1. Yorkshire and The Humber region within the UK.
Source: Wikimedia Commons.[1]

65.5% of total national direct damage (region in red in Fig. 1). Approximately 1800 homes were flooded and more than 4000 people were affected. Additionally, more than 64 businesses, schools and public buildings were flooded, and infrastructure services such as roads and electricity substations suffered significant disruptions as well (Ash et al., 2008).

Traditional assessments of economic losses resulting from disasters of this type consider only direct damages to the physical infrastructure (Veen, 2004; Cole, 2003; Steenge and Bočkarjova, 2007). Nevertheless, it has been well documented that knock-on effects are triggered by these direct damages and that they constitute a considerable share of the total socioeconomic burden of the disaster (Cochrane, 1997; Hallegatte and Przyluski, 2010; Veen, 2004). Therefore, accurate flood risk management requires more than proper assessments of losses from capital and labour productivity disruptions; it must also consider the ripple effects of the recovery process, which are dispersed through sectoral and regional interdependencies.

Knock-on effects can arise in two main ways. On the one hand, damages to capital such as roads and offices will interrupt transportation and further disrupt economic activities, while damages to labour – including injuries and death – can be perceived as losses of labour productivity that ultimately prevent economic functioning. During an economic recovery, both capital and labour should be restored. On the other hand, production loss in a single sector, as a result of either capital or labour productivity losses, affects both customer and supplier industries, namely the 'downstream' and 'upstream' sectors. This indicates that an initial economic loss in a single sector can eventually spill over into the entire economic system and even into other previously unaffected regions through sectoral and regional interdependencies.

Flood risk management[2] requires, first, accurate estimates of losses from both capital and labour productive constraints after a flooding. Second, to estimate a flood's indirect effects on the economy, it is essential to consider the ripple effects resulting from sectoral and regional interdependencies. Flood risk management can also reduce vulnerability and increase the resilience[3] of affected regions in the future. (Okuyama, 2009; Rose, 2004; Veen & Logtmeijer, 2003). Third, all accumulated production losses that occur prior to the full recovery of the economy, as well as the costs of capital and labour restoration during the flood's aftermath, should be taken into consideration.

This paper introduces the new concept of *flood footprint* to describe an accounting framework that measures the total economic impact that is directly and indirectly caused to the productive system, triggered by the flooding damages to the productive factors, infrastructure and residential capital; on the flooded region and on wider economic systems and social networks. This framework can not only capture the economic costs derived from capital and labour productivity losses but also account for the post-disaster recovery process. Here, we define the productivity loss, from capital or labour, as the reduction in the production level of equilibrium at pre-disaster conditions due to constraints in the availability of any of the productive factors, which in the case of the Leontief production functions are capital and labour. This type of production functions is a particular case of constant elasticity of substitution production functions, where the level of production is determined as a function of the productive factors.

In the case of the Leontief production functions (used within the IO modelling), or perfect complements, it is assumed that the proportion of productive factors is fixed, or in other words, the technology is fixed and there is no possibility of substitution between de productive factors (Miller and Blair, 2009). Owing to the above, a constraint in the availability of any of the productive factors will have a proportional effect in the level of production. For instance, the reduction of 10% in the availability of labour force, due to transport disruptions, illness, displacements or other factors after a flooding, would represent a decrease of 10% in the level of production.

Additionally, as the *flood footprint* framework is developed based on an Input-Output (IO) model, it is also able to measure the knock-on effects resulting from sectoral and regional interdependencies. The concept of *flood footprint* will therefore improve upon existing flood risk assessment and better assist professionals working on disaster risk assessment, preparation and adaptation.

This paper constitutes the first empirical application of the flood footprint framework to a real past event. It is evaluated the total economic cost (or *flood footprint*) in the region of Yorkshire and The Humber, caused by the 2007 summer floods in the UK. While, a sensitivity analysis is carried out to provide robustness in the results.

This paper is structured as follows. The next section reviews selected literature on disaster impact analysis. Section 3 describes the methodology and rationale of the flood footprint model. Section 4 presents the data gathering and codification methods used to analyse total economic losses in Y&H resulting from the floods in

[1] Wikimedia Commons (Yorkshire and The Humber region) https://commons.wikimedia.org/wiki/File:Yorkshire_and_the_Humber_in_England.svg.

[2] '[Flood risk management] focuses on reducing the potential adverse consequences of flooding with regard to human health, the environment, cultural heritage and economic activity' (Vanneuvill et al., 2011).

[3] The Intergovernmental Panel on Climate Change (IPCC) defines vulnerability as the 'degree to which a system is susceptible to injury, damage, or harm' and resilience as the 'degree to which a system rebounds, recoups, or recovers from a stimulus' (Burton et al., 2001).

2007. Section 5 presents the main results of the flood footprint assessment. Finally, conclusions are discussed in section 6.

2. Selected literature on the impact assessment of natural disasters

The impact assessment of natural disasters has been a vibrant research area in recent years, many kinds of methodologies are used to do risk analysis based on different theory systems (Chen et al., 2011, 2015; Okuyama, 2007). For example, from the ecological perspective, Chen et al. (2011) developed an information-based model that on the basis of system methodology to assess the ecological risk by eco-environmental hazard. But our research mainly focus on the economic perspective and only consider the economic impact resulted from natural hazard.

2.1. Economic-based methodologies

Based on economic theory, a range of applicable methodologies is applied into natural disaster risk analysis (Okuyama, 2007). However, the pre-eminence of one approach over the others has not yet been decisively determined, and differences in results are influenced by different approaches, assumptions, data, and reference theories (Greenberg et al., 2007). Several methodological adaptations and extensions have arisen, each attempting to overcome the analytical limitations of existing models. The most widely used have been those based on econometrics, Input-Output (IO) analysis, and the Computable General Equilibrium (CGE) model.

Econometric models possess rigorous statistical foundations, which enables forecasting estimations. However, long data series — which are normally at the national level — rarely contain similar past events, which prevents a subnational regional analysis. Additionally, the data hardly distinguish between direct and higher-order — or indirect — losses. These problems hamper the performance of disaster impact analyses (Cochrane, 2004; Greenberg et al., 2007; Hallegatte and Przyluski, 2010; Li et al., 2013; Okuyama, 2007, 2009).

Input-Output based models are founded on the basic idea of the circular flow of the economy in equilibrium. The IO tables present the inter-industrial transactions of the whole economy in a transparent and linear array, which enables the assessment of knock-on effects along the value chain. The analysis remains objective, as the necessary calibration of parameters is usually much lower than in other methodologies. Regionalization of the IO national tables is also possible, thus enabling regional analysis. These characteristics allow the estimation of higher-order losses. Nonetheless, the original IO model presents some limitations: The basic IO model is a static model, the production functions are based on the fixed-proportion approach, the prices are fixed and the substitutions of inputs and imports are not considered. (Cole, 2003; Greenberg et al., 2007; Okuyama, 2007, 2009; Rose, 2004). It is essentially a demand-driven model, and risk uncertainties are not considered in the original version (Cochrane, 2004; Li et al., 2013).

The CGE-based models rely on certain characteristics in overcoming some of the IO rigidities, while retaining the inter-industrial and regional analyses of the IO model. The rigidities are mainly related to the manageability of supply constraints, price changes, non-linearity, and flexibility in input and import substitutions. However, the modelling refinement of CGE models relies on a high number of parameters that are exogenously calibrated. This introduces additional uncertainty and bias into the analysis. In the case of impact analysis, the model assumes that the economy is always in equilibrium, which is one of the main features that the analysis is intended to capture: the economic imbalances and consequences that arise after a disaster.

2.2. Input-Output methodology

Next, we trace the development of IO-based models for impact analysis, as the characteristics of the IO model make it particularly well suited to an economy's situation in the aftermath of a disaster (Cochrane, 2004; Greenberg et al., 2007; Okuyama, 2007, 2009; Rose, 1995, 2004; Veen, 2004).

The first version of the IO model, developed by Wassily Leontief in the 1930s, is a static and demand-driven model. However, the damages caused by a natural disaster impose imbalances in the economy that usually affect the supply side of the productive chain. These imbalances then lead to bottlenecks in production, and damages spill over because of a series of knock-on effects, which ripple through the economic interconnections among industrial sectors and coupled economies. To cope with this, *ad hoc* extensions have been developed to overcome the original rigidities of the IO model and to manage the complexity of natural disaster impact assessment (Cole, 2003; Li et al., 2013; Okuyama, 2007; Rose, 2004).

Initially, to assess the damage to productivity in the industrial sectors, some authors (Y. Haimes and Jiang, 2001; Y. Y. Haimes et al., 2005; J. R. Santos and Haimes, 2004; R. J. Santos, 2006) developed a measure of *expected inoperability* to address the risk inherent in natural disasters. This is a concept based on the system risk or probability of limitations on performing the planned *natural or engineered functions*. Based on this concept, the Inoperability Input-Output model (IIM) assumes a direct relation between the level of transactions and the interdependency among economic sectors. The IIM has been widely used to assess the impact of disasters and has a special focus on disaggregated analysis by economic sector. Nevertheless, some rigidities from the original IO model remain, such as the demand-driven approach, the static analysis and the assumption of economic equilibrium after the disaster, as the IIM is itself a stylized application of the standard IO model (Dietzenbacher and Miller, 2015). In this regard, Oosterhaven (2017) states that the IIM fails to account all the negative impacts from natural disasters and does not consider those positive effects that may arise from additional demand in those sectors/regions substituting the inputs that cannot be supplied by the hit industries.

Leung et al. (2007) and Xu et al. (2011) developed a supply-driven extension for the IIM. These are price models that only capture changes in the prices of the value added factors (labour, taxes, etc.). These models have been useful in the analysis of recovery dynamics after a disaster. Nevertheless, the relation between changes in primary factors' prices and output quantities is not clear. Additionally, Xu et al. (2011) modelled recovery time as an exogenous variable when it is expected to be a result of the impact analysis. Subsequently, J. R. Santos and Rehman (2012) extended the model to estimate the recovery time for the affected sectors based on survey data. One limitation in this model is, however, the absence of institutional allocation options for the remaining resources.

Focusing on post-disaster economic imbalances, Steenge and Bočkarjova (2007) introduce the Event Account Matrix (EAM) concept within IO modelling. This is a mathematical component (a diagonal matrix) whose diagonal-elements express the damaged proportion of each sector's productive capacity.[4] The imbalances and possible bottlenecks after a shock are derived from the information in the EAM, and the recovery path is traced from this point. The model also allows substitutions of *importable* goods and services (Bockarjova et al., 2004; Steenge and Bočkarjova, 2007).

[4] The rationale of the EAM is disclosed in vector form for this paper, the event account vector (EAV).

Regarding the dynamics of the recovery process, even though the basic IO model is static, Leontief himself developed a dynamic extension (Miller and Blair, 2009; Rose, 1995), and other extensions have subsequently been adapted to address this constraint. Two such examples are the Sequential Interindustry Model (SIM) (Okuyama, 2004; Romanoff and Levine, 1981), a continuous-time formulation of a Regional Econometric IO model (REIM), and the Dynamic Inoperability IO model (DIIOM), a dynamic extension of the IIM (Y. Y. Haimes et al., 2005; Okuyama, 2007; J. R. Santos and Rehman, 2012; R. J. Santos, 2006; Xu et al., 2011). These represent notable progress in overcoming the constraints of models used for disaster impact analysis. However, even these improvements do not address the assumption of economic equilibrium in the aftermath of a disaster.

Stéphane Hallegatte (2008) uses a time-scaled approach to model the recovery path. He developed an Adaptive Regional IO (ARIO) model that considers both the bottlenecks caused by damage to industrial productive capacity and the adaptive behaviour of consumers and producers facing such imbalances. Nevertheless, the model does not consider the bottlenecks resulting from constraints in labour's productive capacity, nor does it consider residential capital damage (Li et al., 2013).

Based on the former ARIO model, Li et al. (2013) laid the foundations for the *flood footprint* model. This incorporates production restrictions — not only based on industrial damage but also considering reductions in productivity as a result of labour damage. The model also considers residential damage, which interacts with the reconstruction process during the competition for available resources and affects the recovery of labour capacity.

An alternative methodology to account the effects from changes in intermediate inputs (as in a flooding event) is developed by Dietzenbacher & Lahr (2013). They apply the method of hypothetical extractions to the analysis of impact assessment. The method proposes to *extract*, partially or totally, the intermediate transactions of a sector within the economy. This is, replacing the row or column of the affected sector with zeros (or smaller proportions of the original value). A new level of production is calculated under this condition. The difference with the original level of production constitutes the effect of the disaster in the economy. The main contribution of this approach is, in a consistent way, considering the forwards effects of a shock within the demand-driven IO model. However, Oosterhaven and Bouwmeester (2016) have argued that the assessment of forward effects with this method is faulty, as what it is measured is the backwards effects of the reduction of intermediate sales of an industry. And not the forward effects of the reduction of inputs from the affected industry to the other purchasing industries. Although it provides with a method to account for supply chain disruptions, within the IO framework, it fails in accounting for other effects when an economy faces a natural disaster, such as the damage in non-productive sectors (or residential damages), and disruptions in productive capacity due to constraints in labour force.

More recently, Koks et al. (2014) have used a Cobb-Douglas function to estimate the direct damages from labour and capital constraints, and the indirect damages incurred during the recovery process are derived through the ARIO model. This approach constitutes a good comparison for the flood footprint model, as it also incorporates restrictions in the productive capacity of labour using a different approach.

A new approach developed by Oosterhaven and Bouwmeester (2016) is based on a non-linear program that minimises the information gain between the pre-disaster and post-disaster situation of economic transactions. The model is successful in reproducing the recovery towards the pre-disaster economic equilibrium. The model has been tested just hypothetically and further development is to be done for applications to real cases. Some aspects of disaster impact analysis are left aside, as the damage to residential capital, or the recovery of productive capacity of labour.

Considering the existing models used in disaster impact analysis, this paper applies the new concept of *flood footprint* to measure the total socioeconomic impact that was directly and indirectly caused by the 2007 summer floods in the Y&H region. This new damage accounting framework combines the advantages of existing models used in disaster risk analysis, including the analysis of capital damages by industrial sector as well as labour constraints; it also considers post-disaster economic imbalances and supply bottlenecks. To model the recovery process, the allocation of resources through a rationing scheme is proposed to satisfy the restoration of industrial capital and households' damages. The possibilities of changes in final demand are also accounted for through the modelling of consumers' adaptive behaviour.

3. Flood footprint assessment framework

In this section, the rationale of the *flood footprint* model is disclosed in detail. Regarding the mathematical symbols and formulae, matrices are represented by bold-italic capital letters (e.g., $\boldsymbol{X}$), vectors by bold-italic lowercase (e.g., $\boldsymbol{x}$) and scalars by italic lowercase (e.g., x). By default, vectors are column vectors, with row vectors obtained by transposition (e.g.x'); a conversion from a vector (e.g., $\boldsymbol{x}$) to a diagonal matrix is expressed as a bold lowercase letter with a circumflex (i.e.$\hat{\boldsymbol{x}}$); the operators '.*' and './' are used to express element-by-element multiplication and the element-by-element division of two vectors, respectively.

The IO model is founded on the basic idea of the circular flow of an economy in equilibrium. The IO tables present the inter-industrial transactions of the whole economy in a linear array. In mathematical notation it is presented as:

$$\boldsymbol{x} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{f} \tag{1}$$

Where $\boldsymbol{x}$ is a vector of dimension $1xn$ (where n is the number of industry sectors) representing the total production of each industrial sector,[5] $\boldsymbol{Ax}$ represents the intermediate demand vector, where each element of the matrix $\boldsymbol{A}$, $[a_{ij}]$, refers to the technical relation showing product i needed to produce one unit of product j. Finally, $\boldsymbol{f}$ indicates final demand vector of products.

Based on the IO modelling, the assessment of the damage by the *flood footprint* modelling departs from the *Basic Equation* concept coined by Steenge and Bočkarjova (2007). This is a closed[6] IO model that represents an economy in equilibrium. The equilibrium implies that total production equals total demand with the full employment of productive factors, including both capital and labour, as in equation (2).

$$\begin{bmatrix} \boldsymbol{A} & \boldsymbol{f}/l_T \\ \boldsymbol{l}' & 0 \end{bmatrix} \begin{pmatrix} \boldsymbol{x} \\ l_T \end{pmatrix} = \begin{pmatrix} \boldsymbol{x} \\ l_T \end{pmatrix} \tag{2}$$

$$\text{and } l_T = \boldsymbol{l}'\boldsymbol{x} \tag{3}$$

where $\boldsymbol{l}'$ is a row vector of *technical labour* coefficients for each industry, showing the relation of labour needed in each industry to produce one unit of product.: $\left[\frac{l_i}{x_i}\right]$ l_i is the industrial level of

[5] In the modelling, it is assumed that each sector produces only one uniform product.

[6] Here, *closed* means that the primary productive factors (labour) are explicitly considered within the model.

employment. The scalar l_T is the total level of employment in the economy.

All inter-industrial flows of products as well as industrial employment are considered as the necessary inputs involved in the production of each unit of output. A linear relation between the productive factors (labour and capital) and the output in each sector is assumed in IO analysis, suggesting that inputs should be invested in fixed proportions for proportional expansion in output.

However, this equilibrium is broken after a disaster, and inequalities arise between productive capacity and demand. In the next section, we introduce the possible sources of these inequalities.

3.1. Sources of post-disaster inequalities

After a disaster, market forces become imbalanced, leading to gaps between supply and demand in different markets. The causes of these imbalances may be varied, and they constitute the origin of the ripple effects that permeate the economy of the flooded region.

3.1.1. Labour productivity constraints

The production functions in the IO model assume a complements-type technology where the productive factors — labour and capital — maintain a fixed relationship in the production process. Constraints in any of the productive factors will produce, therefore, a proportional decline in productive capacity, even when other factors remain fully available. Therefore, labour constraints after a disaster may impose severe knock-on effects on the rest of the economy. This makes labour constraints a key factor to consider in disaster impact analysis. In the *flood footprint* model, these constraints can arise from employees' inability to work as a result of illness or death, or from commuting delays due to damaged or malfunctioning transport infrastructure. In the model, the proportion of surviving production capacity from the constrained labour productive capacity ($\boldsymbol{x}_l^t$) after the shock is:

$$\boldsymbol{x}_l{}^t = (\boldsymbol{i} - \gamma_l^t).*\boldsymbol{x}^0 \tag{4}$$

$$\text{and } \gamma_l^t = \left(\boldsymbol{l}^0 - \boldsymbol{l}^t\right)./\boldsymbol{l}^0 \tag{5}$$

where $\boldsymbol{\gamma}_l^t$ is a vector where each element contains the proportion of labour that is unavailable at each time t after the flooding event. The vector $\boldsymbol{i}$ is a vector of ones of the same dimension as γ_l^t, so that the vector $(\boldsymbol{i} - \gamma_l^t)$ contains the surviving proportion of employment at time t. $\boldsymbol{x}^0$ is the pre-disaster level of production.

The proportion of the surviving productive capacity of labour is thus a function of the loss from the sectoral labour force and its pre-disaster employment level. Following the fixed proportion assumption of the production functions, the productive capacity of labour after the disaster ($\boldsymbol{x}_l^t$) will be a linear proportion of the surviving labour capacity at each time step.

3.1.2. Capital productivity constraints

Similar to labour constraints, productive capacity from industrial capital during the flooding aftermath ($\boldsymbol{x}_{cap}^t$) will be constrained by the surviving capacity of the industrial capital. The share of damage to each sector are disclosed in the event account vector (EAV), following Steenge and Bockarjova (2007) Then, the remaining production capacity of industrial capital at each time-step, is:

$$\boldsymbol{x}_{cap}^t = \left(\boldsymbol{I} - \gamma_{cap}^t\right)*\boldsymbol{x}^0 \tag{6}$$

$$\text{and } \gamma_{cap}^t = \left(\boldsymbol{k}^0 - \boldsymbol{k}^t\right)/\boldsymbol{k}^0 \tag{7}$$

where, $\boldsymbol{x}^0$ is the pre-disaster level of production, γ_{cap}^t is the EAV, a column vector showing the share of damages of productive capital in each industry. $\boldsymbol{k}_0$ is the vector of capital stock in each industry in the pre-disaster situation, $\boldsymbol{k}^t$ is the surviving capital stock in each industry at time t during the recovery process.

During the recovery, the productive capacity of industrial capital is restored gradually through both local production/reconstruction and imports.

3.1.3. Post disaster final demand

On the other side of the economic system, final demand may vary for diverse reasons. On the one hand, the recovery process involves the reconstruction and replacement of damaged physical capital, which increases the final demand for those sectors involved in the reconstruction process, namely, the *reconstruction demand*, $\boldsymbol{f}_{rec}$. On the other hand, final demand may also decrease after a disaster. Based on Li et al. (2013), it has been noted that after a disaster, strategic adaptive behaviour would lead people to ensure their continued consumption of basic commodities, such as food and medical services, while reducing consumption of other non-basic products.

In the model, we consider the adaptive consumption behaviour of households. Here, the demand for non-basic goods is assumed to decline immediately after the disaster, while consumption in industries providing food, energy, clothing and medical services remains at pre-disaster levels.

Recovery in household consumption is driven by two complementary processes. For consumption adaptation, we consider a short-run tendency parameter ($\mathbf{d}_1^t$), which is modelled as the rate of recovery in consumption at each time step. The rationale here is that consumers restore their consumption according to market signals about the recovery process. Likewise, a long-run tendency parameter ($\mathbf{d}_2^t$) is calculated as a *recovery gap,* i.e., the total demand minus the total production capacity compared against the total demand at each time step. These two parameters are calculated for each sector. So, the expression for dynamic household consumption recovery is:

$$\boldsymbol{f}_{hh}^t = \left(\mu^0 + \boldsymbol{d}_1^t + \boldsymbol{d}_2^t\right).*\mathbf{c}^0 \tag{8}$$

where the parameter μ^0 is a scalar which expresses the reduced proportion of household demand (a parameter similar to the EAV) over time, and the vector $\mathbf{c}^0$ represents the pre-disaster level of household expenditure on products by industrial sector.

The rest of the final demand categories recover proportionally to the economy, based on the share of each category regarding pre-disaster final demand. It should be noted the trade-off of resources allocation between final demand and the reconstruction process. The adapted total final demand ($\boldsymbol{f}^t$), then, is modelled as follows:

$$\boldsymbol{f}^t = \sum_k \boldsymbol{f}_k^t + \boldsymbol{f}_{rec}^t \tag{9}$$

where $\mathbf{f}^t$ is the adapted total final demand at each time step t, including the reconstruction demand for damaged industrial and residential capital ($\boldsymbol{f}_{rec}^t = \boldsymbol{f}_{cap}^t + \boldsymbol{f}_{hh}^t$). It also includes the final demand for all final consumption categories, indicated by the summation $\sum_k \boldsymbol{f}_k^t$, where the subscript k refers to the vector of each category of final consumption: $k = 1$ is for the adapted household consumption ($\boldsymbol{f}_{hh}^t$), $k = 2$ is for government expenditure, $k = 3$ is for investment in capital formation, and $k = 4$ is for external consumption or exports.

The adapted total demand for each sector, ($\boldsymbol{x}_{td(i)}^t$), can thus be calculated as follows:

$$x_{td(i)}^t = \sum_{j=1}^{n} a_{ij} x_{td(i)}^t + f_i^t \tag{10}$$

Equations (4)–(10) describe the changes on both sides of the economy's flow – production and consumption – where imbalances in the economy after a disaster arise from the differences in the productive capacity of labour, the productive capacity of industrial capital, and changes in final demand. From this point, the restoration process starts to return the economy to its pre-disaster equilibrium production level.

3.2. Post-disaster recovery process

The following section describes the process of recovery. Here, an economy can be considered as recovered once labour and industrial production capacities are in equilibrium with total demand and production is restored to the pre-disaster level. How to use the remaining resources to achieve pre-disaster conditions is modelled based on a selected rationing scheme.

The first step is to determine the available production capacity in each period after the disaster. Within the context of Leontief production functions, the productive capacity is determined for the minimum of either productive factor, capital and labour, as shown below:

$$\boldsymbol{x}_{tp}^t = min\left\{\boldsymbol{x}_{cap}^t, \boldsymbol{x}_l^t\right\} \tag{11}$$

Secondly, the level of the constrained production capacity is compared with the total demand to determine the allocation strategy for the remaining resources and for reconstruction planning. The rules of this process constitute what it is called the *rationing scheme*, described below.

3.2.1. Rationing scheme

The recovery process requires allocating the remaining resources to satisfy society's needs during the disaster's aftermath. Thus, the question of how to distribute and prioritize the available production based on the remaining capacity of industry or final customer demand becomes essential, as recovery time and indirect costs can vary widely under different rationing schemes.

This case study used a *proportional-prioritization* rationing scheme that first allocates the remaining production among the inter-industrial demand ($\boldsymbol{Ax}_{tp}^t$) and then attends to the categories of final demand.[7] This assumption is built on the rationale that business-to-business transactions are prioritised, based on the observation that these relations are stronger than business-to-client relationships (Stéphane Hallegatte, 2008; Li et al., 2013).

Thus, when calculating the productive possibilities of the next period, actual production is first compared with inter-industrial demand. Defining $o_i^t = \sum_j A_{ij} x_{tp(j)}^t$ as the production required in industry i to satisfy the intermediate demand of the other industries, two possible scenarios may arise after the disaster (Hallegatte, 2008):

The first scenario occurs if $x_{tp(i)}^t < o_i^t$, in which case the production from industry i at time t in the post-disaster situation ($x_{tp(i)}^t$) cannot satisfy the intermediate demands of other industries. This situation constitutes a bottleneck in the production chain, where production in industry j is then constrained by $\frac{x_{tp(i)}^t}{o_i^t} x_{tp(j)}^t$, where $\frac{x_{tp(i)}^t}{o_i^t}$ is the proportion restricting the production in industry j, $x_{tp(j)}^t$.

This process proceeds for each industry, after which there must be consideration of the fact that industries producing less will also demand less, in turn affecting and reducing the production of other industries. The iteration of this process continues until production capacity can satisfy this *adapted* intermediate demand and some remaining production is liberated to satisfy part of the final and *reconstruction* demand and increase the productive capacity the next period. This situation leads to a partial equilibrium, where level of the adapted intermediate demand is defined as $\boldsymbol{Ax}_{tp}^{t^*}$, where the asterisk in $\boldsymbol{x}_{tp}^{t^*}$ represents the adapted production capacity that provides the partial equilibrium, and is smaller than the actual production capacity ($\boldsymbol{x}_{tp}^t$) from equation (11).

This process continues until the total production available at each time, $x_{tp(i)}^t$, can satisfy the intermediate demand at time t, o_i^t.

The second scenario occurs when $x_{tp(i)}^t > o_i^t$. Then, the intermediate demand can be satisfied without affecting the production of other industries.

In both cases, the remaining production after satisfying the intermediate demand is proportionally allocated to the recovery demand and to other final demand categories in accordance with the following expressions:

$$\left(\boldsymbol{x}_{tp}^{t*} - \boldsymbol{A} * \boldsymbol{x}_{tp}^t\right) .* \boldsymbol{f}_k^0 . \Big/ \left(\sum_k \boldsymbol{f}_k^0 + \boldsymbol{f}_{rec}^t\right) \tag{12}$$

$$\left(\boldsymbol{x}_{tp}^{t*} - \boldsymbol{A} * \boldsymbol{x}_{tp}^t\right) .* \boldsymbol{f}_{rec}^t . \Big/ \left(\sum_k \boldsymbol{f}_k^0 + \boldsymbol{f}_{rec}^t\right) \tag{13}$$

Equation (12) refers to the distribution of product to the k categories of final demand, while equation (13) refers to the proportion of available product that is designated to reconstruction.

The expression ($\boldsymbol{x}_{tp}^t - \boldsymbol{A} * \boldsymbol{x}_{tp}^t$) refers to the production left after satisfying the intermediate demand, and $\sum_k \boldsymbol{f}_k^0$ refers to the total final demand in the pre-disaster period, so that the production left after satisfying intermediate demand is allocated among the categories of final demand following the proportions of pre-disaster condition, plus the consideration of the reconstruction needs for recovery ($\boldsymbol{f}_{rec}^t$). Note that for the first scenario, the expression $\mathbf{A} * \mathbf{x}_{tp}^t$ becomes $\mathbf{A} * \mathbf{x}_{tp}^{t*}$ and represents the *adapted intermediate demand*, where $\boldsymbol{x}_{tp}^{t^*}$ is smaller than the actual production capacity, $\mathbf{x}_{tp}^t$.

Additionally, we assume that part of the unsatisfied final demand is covered by imports, some of which contribute to the recovery when allocated to *reconstruction demand*.

[7] We assume here that the productivity of any of the productive factors does not change during the recovery process, as is the case with Leontief production functions. We also assume that the disaster happens just after time t = 0 and that the recovery process starts at time t = 1.

3.2.2. Imports

In the *flood footprint* model, imports help in the reconstruction process by supplying some of the inputs that are not internally available to meet *reconstruction* demand. Additionally, if the damaged production capacity is not able to satisfy the demand of final consumers, they will rely on imports until internal production is restored and they can return to their previous suppliers.

There are some assumptions underlying imports. First, imports will be allocated proportionally among final demand categories and reconstruction demand. Second, commodities from other regions are assumed to be always available for provision at the maximum rate of imports under the pre-disaster condition. Third, there are some types of goods and services that, by nature, are usually supplied locally (such as utilities and transport services), making it infeasible to make large scale adjustments over the time scale of disaster recovery. Finally, imports are assumed to be constrained by the total *importability capacity,* which here is defined as the survival productive capacity of the transport sectors (see equation (14)). The assumption is that the capacity of transporting goods is proportional to the productive capacity of the sectors related with transport, so that if the production value of sectors related with transport services is contracted by x% in time t, the imports will contract by the same proportion, in reference to the pre-disaster level of imports, $\boldsymbol{m}^t$.

$$\boldsymbol{m}^t = \left(\frac{x_{tran}^{*(t)}}{x_{tran}^0} * \boldsymbol{m}^0\right) \tag{14}$$

where $\mathbf{m}^0$ is the vector of pre-disaster imports, and x_{tran}^0 and $x_{\text{tran}}^{*(t)}$ are the scalars denoting the pre-disaster and post-disaster production capacities of the sectors related with transport. The subscript *tran* refers to aggregated transport sectors by land, water and air. If sectors related with transport are 2 or more, then x_{tran}^0 is the sum of the product of those sectors at pre-disaster level, and $x_{\text{tran}}^{*(t)}$ is the product of those sectors at time t during recovery, obtained from the vectors of productive capacity, $\mathbf{x}^0$ and $\mathbf{x}^{*(t)}$, respectively.

3.2.3. Recovery

Decisions to return to pre-disaster conditions can be complex and varied. Here, we have assumed a way of adapting to a condition of balanced production and demand. That is, we pursue a partial equilibrium for productive capacities at each time period – through the rationing scheme – and then follow a long-term growth tendency towards the pre-disaster level of production – through the reconstruction efforts.

It should be remembered that the recovery process implicates the repair and/or replacement of the damaged capital stock and households. During this process, production capacity increases both through local production and through imports allocated to *reconstruction demand*.

Then, the productive capacity of each industry for the next period incorporates the rebuilt capacity of the last period:

$$x_{cap(i)}^{t+1} = x_{cap(i)}^t + \Delta x_{cap(i)}^t \tag{15}$$

$$\text{where: } \Delta x_{cap(i)}^t = g_i \left\{ \left[m_i^t + \left(x_{tp(j)}^t - \sum_{j=1}^n a_{ij} x_{tp(j)}^t \right) \right] * \left[f_{cap(i)}^t \Big/ \left(\sum_k f_{k(i)}^0 + f_{rec(i)}^t \right) \right] \right\}$$

where g_i encloses the functional relation (or ratio) between capital and production to each sector, and the argument of the function represent the amount of resources invested in capital reconstruction by sector. And where $m_i^t + (x_{tp(j)}^t - \sum_{j=1}^n a_{ij} x_{tp(j)}^t)$ is the total product (regional and imported) allocated to final consumption, while the expression $f_{cap(i)}^t \,/\, (\sum_k f_{k(i)}^0 + f_{rec(i)}^t)$ refers to how much of that product is allocated to capital reconstruction each time period.

Note that the proportion of affected capital –the EAV– changes for each sector by the amount:

$$\gamma_i^t - \gamma_i^{t+1} = \frac{\left[m_i^t + \left(x_{tp(i)}^t - \sum_{j=1}^n a_{ij} x_{tp(j)}^t \right) \right] * \left[f_{cap(i)}^t \Big/ \left(\sum_k f_{k(i)}^0 + f_{rec(i)}^t \right) \right]}{f_{rec(i)}^0} \tag{16}$$

The new level of production is compared with the level of labour capacity at the next time-step. Then, the process described above is repeated until an equilibrated economy of the pre-disaster production level is reached.

The driving forces of recovery are constituted, then, by the progressive restoration of the productive capacity of industrial capital by means of internal production and imports allocated to *reconstruction* demand, by the restoration of the labour force, and by the recovery of final demand.

3.3. Flood footprint modelling outcomes

The flood footprint model provides us with the outcomes of diverse economic variables over the course of the recovery process. All results are provided at each time-step during restoration and at a disaggregation level of 46 industrial sectors. The time that each variable and sector requires to achieve its pre-disaster level is, likewise, provided by the model.

Results of the *direct* and *indirect damages* constitute the principal outcomes of the model.

The *direct damages* account for the value and the proportion of the damages to the physical infrastructure, both to industrial and residential capital. To determine these, we construct the EAV with the proportion of damage to the capital stock as the cost of reconstruction. The model, in turn, translates the damage from this *stock variable* into damages to productivity, a *flow variable*.

The *indirect damages* account, period by period, for non-realised production owing to constraints in both productivity and demand, i.e., the cascading effects from the *direct damages*.

The model delivers the dynamics of recovery for other variables, including industrial productive capacity as rebuilt capital; labour productive capacity, which is linked to the restoration of residential capital and transportation facilities; the contribution of imports to the economy during the recovery process (as the proportion of final demand satisfied by external suppliers and of production allocated to reconstruction, both of which are processes also linked to the process of transport restoration); and final demand, as the restoration of levels of consumption in each category, which is influenced by adaptive behavioural modelling for the case of household consumption.

It should be considered that the trajectories of the variables' recoveries are influenced by the assumptions and decisions considered for reconstruction, such as the establishment of the rationing scheme. On the other hand, a sensitivity analysis of the parameters is performed to obtain robust results and to determine how the results are influenced by changes in the parameters.

4. Data gathering and codification

The Flood Footprint model requires two sets of data: economic data about the affected region and information about the disaster. All of the values are for 2007, and when they are monetary they are in millions of pounds (£million) at 2009 prices. A monthly time scale is used for the temporal analysis, and the sectoral disaggregation uses 46 economic sectors (see sectors disaggregation in the EAV provided in the appendix).

4.1. Economic data

The economic data include information on capital stock, final demand, employment, and inter-industrial transactions. All the information is at the regional level, and when available it was obtained from official data; otherwise, a regionalization was carried out.

Capital stock data are only available at the national level. The regionalization consisted of obtaining the productivity of each sector at the national level and then adjusting by regional output, assuming the same productivity as the national average. The regional dwelling capital is the proportion of housing in the region multiplied by the national dwelling capital. For the region of Y&H, this accounts for 8%.

The categories for final demand, i.e., households, government, capital, imports and exports, were obtained from the UK-Multisectoral Dynamic Model (MDM) by Cambridge Econometrics Ltd,[8] a macro-econometric model used to analyse and forecast environmental, energy and economic data for twelve regions in the UK. The data used for the analysis were for the region of Y&H and 46 industry sectors.

Employment data are usually available at a very detailed regional scale; thus, these data were obtained directly from official data. However, the sectoral disaggregation was not consistent with the rest of the data. To match the data with the 46-sector disaggregation, a weighted distribution was followed based on both national employment and the value-added data from the MDM.

For inter-industrial transactions data, a regionalised matrix of technical coefficients had to be derived from the national IO tables following the methodology developed by Flegg and Webber (2000), owing to the lack of regional tables (see supporting information for the regionalization technique). The transactions' values are obtained later by multiplying the regional matrix of technical coefficients by the regional output.

4.2. Disaster data

Ideally, the disaster data comprise information of damages to industrial capital, residential capital, and infrastructure; reductions in labour capacity; and changes in final demand.

The main source for the disaster data is the UK Environmental Agency, and the information for the analysed event is disclosed in the report 'Economic Impacts of Flood Risk on Yorkshire and Humber. Cost of 2007 Floods' (Ash et al., 2008).

For damages to industrial capital, the report states a total cost of £380 million for business premises, stock, equipment, etc. Additionally, the £470 million of damages to infrastructure are allocated to *infrastructure* sectors, namely Transport, IT services, Electricity & Gas, Water & Sewerage & Waste, PAD, and Education and Health sectors. As the sectoral disaggregation was for 15 categories, an allocation of damage to each sector was made through a weighted distribution based on the share of the sector in the regional economy. These data were compared with stocks of industrial capital to determine the proportion of affected productive capacity, i.e., the values of the EAV (see Appendix for the values of the EAV for each industry).

Regarding residential damage, 10,759 houses were reported flooded, representing 0.6% of total housing in the region. Total household damages were estimated at £340 million by the UK Environmental Agency.

Labour constraints, about which hard data are unavailable, were derived from the number of flooded houses multiplied by the average number of working people per household. Additionally, commuting delays were proportionally related to damage in the transport sectors. This resulted in one tenth of the proportional effect in transport, as a proportion of affected labour, and a delay of 1 h in commuting for 1.5% of the regional population.

Finally, as information on changes in final demand is very scarce, we follow a sensitivity analysis over different levels of reduction in non-basic products. The values for the analysis show a decrease of 0.25% in households' demand for non-basic industries and a recovery time of 6 months with positive and marginally decreasing growth, i.e., a higher recovery rate for the first periods, which slows down at the end of the recovery.

5. Results

5.1. Total economic loss for Yorkshire and The Humber region

The Y&H region is located in the north-western region of the UK. The annual GVA in 2007 was over £88 billion (at 2009 prices), which represents around 7% of total UK's value added for that year. Likewise, there are around 2.6 million employees in the region, which constitute over 8% of the total UK's labour force.

According to the flood footprint analysis, it takes at least 14 months for the economy of the Y&H region to return to its pre-disaster situation after the 2007 summer floods in the UK (Fig. 2); this recovery entails both achieving economic equilibrium and returning to pre-disaster production levels. This entails a total economic loss of £2.7 billion, which is equivalent to 3.2% of the regional annual gross value added (GVA).

In differentiating direct economic loss from indirect economic loss, Fig. 2 compares the shares of each category. The direct economic loss (including industrial and residential infrastructure damages) accounts for 1.4% of the yearly GVA (nearly £1.2 billion), of which the majority corresponds to industrial and infrastructural damages (71%). The indirect economic loss – including all non-realised product flow owing to productivity and demand

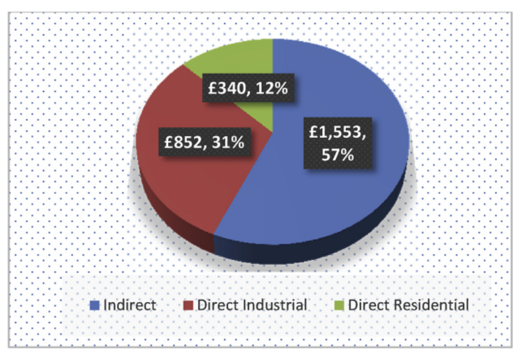

Fig. 2. Flood Footprint damage composition (£million).

[8] http://www.camecon.com/how/mdm-e3-model/.

shortages – accounts for an additional 1.8% of the city's GVA, at around £1.5 billion. This represents 57% of the total flood footprint.

5.2. Economic recovery

The present section describes the progress of the economic variables involved in the recovery process.

Figure 3a) depicts the accounting of the cumulative damage during the recovery process. The area in purple, which indicates the distance between the final demand met by the available production at each time step and the pre-disaster level, represents the total indirect damage over the course of the recovery process. It can be noted that the initial shock represents a decrease of 0.4% of the productive capacity. The shape of the curve shows a fast recovery in the beginning, especially in the first 4–5 months, at which time the economy has recovered approximately 90% of its damaged productive capacity. It must be noted, however, that the recovery-curve shape is influenced by the rationing scheme chosen for the modelling, where the inter-industrial and recovery demand is prioritised over other final demand.

Figure 3b) displays the recovery process of productive capacity, including both labour and industrial capital capacities. The figure indicates that industrial capital constraints constitute the main source of production disruptions in the first period after the disaster, being responsible for the 0.4% fall in productivity. However, this recovers rapidly, and labour disruptions happen to be the main constraint on productive capacity.

Fig. 3 c depicts the dynamics of final demand in the aftermath of the disaster. The green line indicates the adaptation and recovery process of the final demand. This variable includes the adapted behaviour of final consumers and the reconstruction demand. On the other hand, the red line shows how much of that adapted demand can be supplied by the actual constrained capacity of production. Part of the demand that cannot be satisfied by internal production is supplied through imports, as the black line illustrates.

Finally, Fig. 3 d indicates the inequalities that remain between the level of production required by the final demand during the recovery process and the product supply from the surviving production capacity during the aftermath.

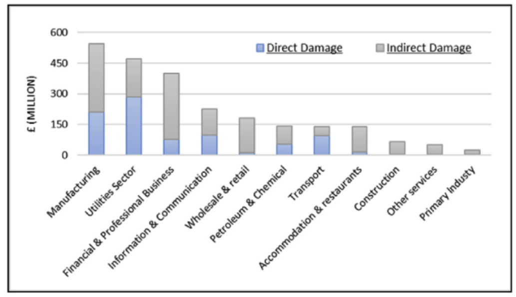

Fig. 4. Sectoral distribution of damage.

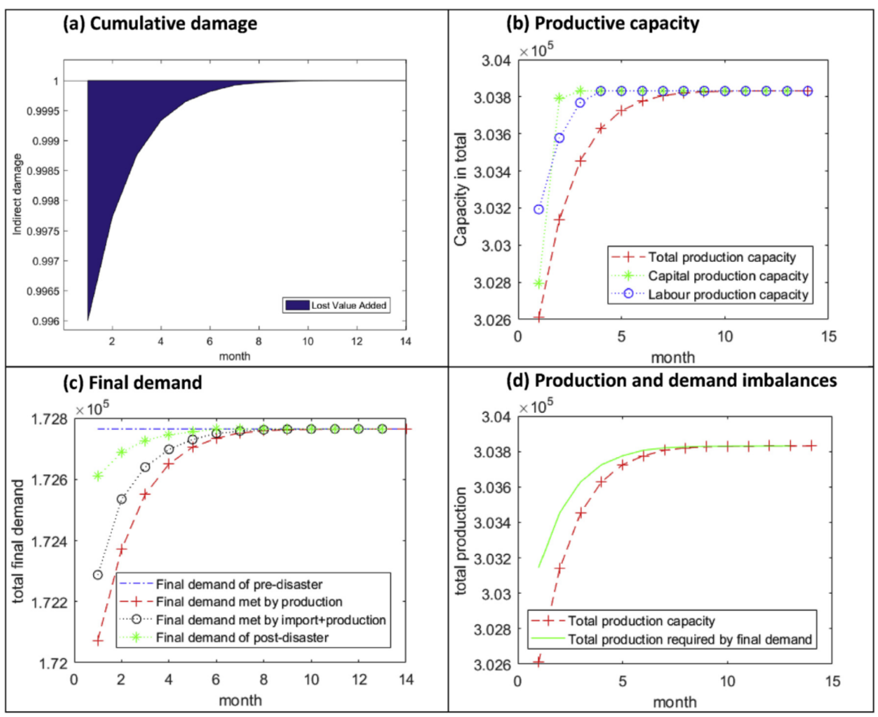

Fig. 3. Recovery process.

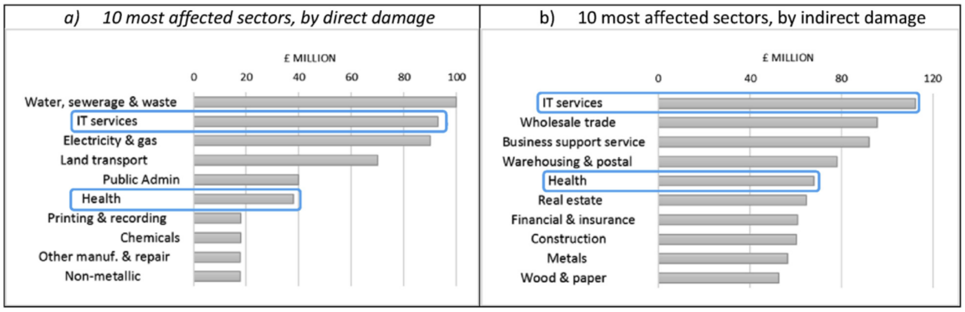

Fig. 5. The most affected sectors by different damage categories: Direct and Indirect damage.

5.3. Sectoral analysis

Because it is based on the IO model, one of the strengths of the flood footprint framework is its capacity to provide an analysis at the industrial sector level. This is especially useful for disentangling the distribution of the knock-on effects as they propagate through the impacted economy and through other economic systems. Additionally, this capacity of the flood footprint framework becomes very convenient when planning for flood risk management and adaptation policies.

Fig. 4 shows the distribution of the *flood footprint* for both direct and indirect damages among ten industrial groups. The proportions of direct and indirect loss present high heterogeneity among the sector groups. For example, Manufacturing is shown to be the most

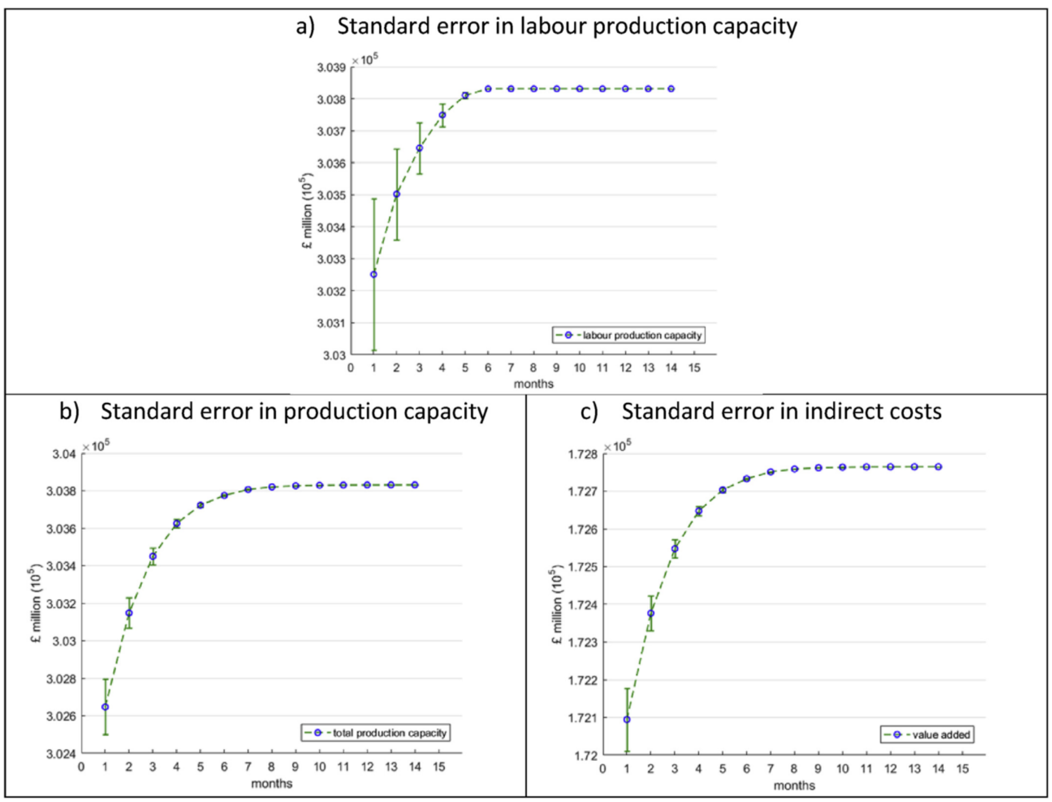

Fig. 6. Sensitivity analysis for labour parameters.

affected sector, with a share of indirect loss 60% higher than direct loss, and the total damages in this group account for 23% of the total *flood footprint*. The utilities sector suffers major direct damages (£190 million), as infrastructure damages are allocated among this sector. The Financial & Professional sector is the most indirectly affected, with 21% of total indirect damages, while just 9% of total direct damages are concentrated in this group (see Fig. 5).

At a more disaggregated level (46 sectors), Fig. 4 depicts the ten most affected sectors for direct (a) and indirect (b) economic losses, respectively. The major direct damage is concentrated in those sectors forming the *Utilities Sector* group. The most affected sector is Water, Sewerage & Waste, accounting for 35% of direct economic loss in the Utilities Sector group and 12% of the total direct damage. Regarding indirect damages, the IT services sector, from the Information & Communication group sector, was the most damaged, accounting for 86% of this group's losses and 11% of the total indirect damages.

Finally, it is noteworthy that two sectors appear in both categories: the IT Services and Health sectors. This indicates they are among the most vulnerable sectors in the region. The flood footprint in these sectors accounts for 13% of the total flood footprint.

5.4. Sensitivity analysis

Uncertainty in the model mainly comes from the lack of data in labour and final demand variables, and some assumptions applied to calibrate the correspondent parameters. To prove the robustness of the results, a sensitivity analysis is performed on labour and final demand parameters.

The sensitivity analysis comprises the upwards and downwards variation of 30% of the parameters in intervals of 5%.

5.4.1. Changes in labour parameters

The variation of parameters comprises the proportion of labour not available for traveling, and the proportion and time of labour delayed by transport constraints.

The results of the sensitivity analysis, as presented in Fig. 6, show that variations in labour parameters have a less-than-proportional effect in indirect costs and the total production capacity, and these are decreasing over time. Other variables are not affected by variations in labour parameters.

The standard deviation of the total variation of labour productive capacity is about £483 million, which causes a standard

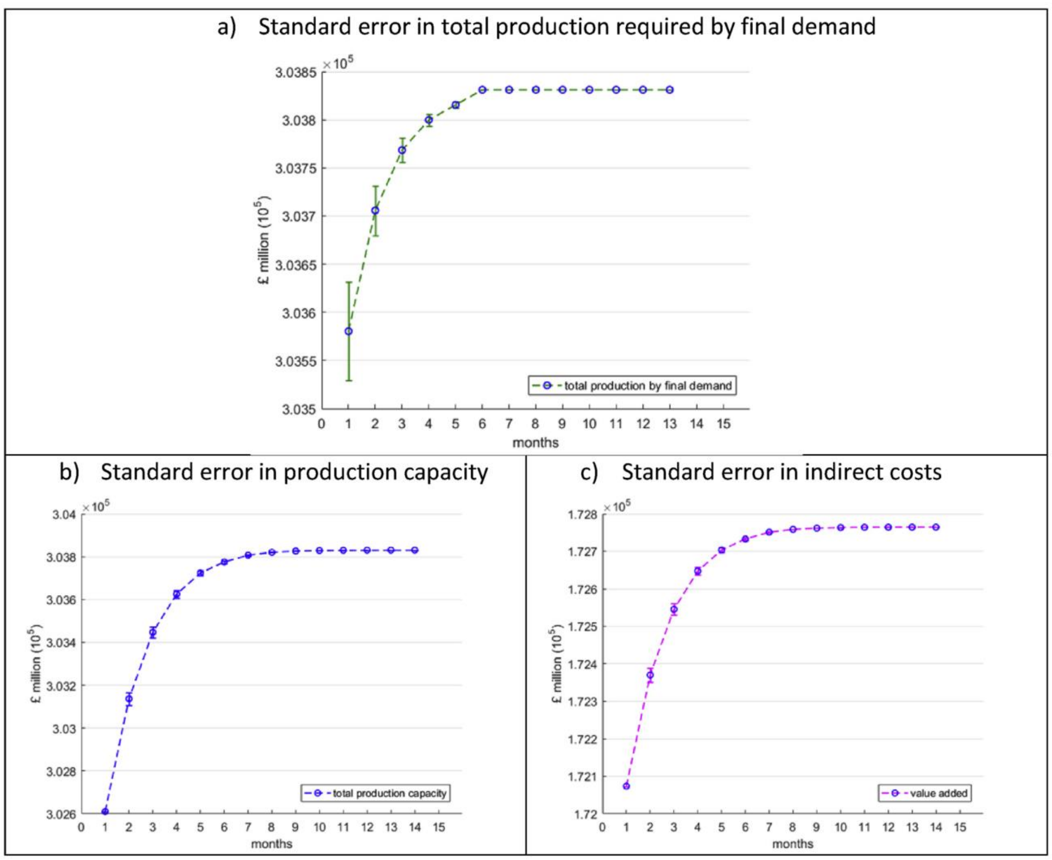

Fig. 7. Sensitivity analysis for final demand parameters.

deviation of £297 million in total production capacity, and a standard deviation of $168 million in indirect damages.

5.4.2. Changes in final demand

The variation of parameters comprises the decreased proportion of consumption in non-basic products.

The results of the sensitivity analysis, as presented in Fig. 7, show that variations in final demand parameters have a less-than-proportional effect in indirect costs and the total production capacity, and these are decreasing over time. Other variables are not affected by variations in labour parameters.

The standard deviation of the total variation of total production required by final demand is about £96 million, which causes a standard deviation of £93 million in total production capacity, and a standard deviation of $54 million in indirect damages.

6. Conclusions

The increasing frequency and intensity of weather-related disasters require more accurate and comprehensive information on damages. This will support better risk management and adaptation policies to achieve economic sustainability in the affected cities in the upcoming years. For instance, the 2007 summer floods caused a national emergency in England, and Yorkshire and the Humber was the most affected region.

This paper is the first study to apply the flood footprint framework to a real past event, the 2007 summer floods in the Yorkshire and The Humber region. This analysis supports the important lesson that losses from a disaster are exacerbated by economic mechanisms, and that knock-on effects (or indirect damage) constitute a substantial proportion of total costs and that some of the most affected sectors can be those that are not directly damaged. For this case study, the proportion of indirect damages accounts for over half of the total flood footprint. The sensitivity analysis proves the stability of the model and the robustness of results.

This research provides a quantitative evidence for policy stakeholders that any direct damage may incur significant indirect impact along the economic supply chain. The climate change adaptation policy should start to consider minimising indirect impact, especially those sectors hidden in the supply chain which are vulnerable to labour loss, such as the services sectors. Not considering the indirect effects would mislead for actions in flood risk management and would lead to an inefficient use of resources.

There are, however, some caveats that must be noted. The current study is subject to some degree of uncertainty. First, data scarcity is the main source of uncertainty, making the use of strong assumptions unavoidable in certain cases. Engineering flood modelling and GIS techniques have been rapidly evolving in recent years, providing new sources of information with great precision and constructing the so-called damage functions,[9] although this progress has demanded substantial computing, time and monetary resources. The implementation of these techniques in future research would considerably improve the accuracy of the analysis. Second, although the model effectively accounts for knock-on effects in the affected regional economy, global economic interconnectedness requires us to move the analysis towards a multi-regional approach if we are to make an exhaustive impact assessment. Finally, additional research on labour and consumption recovery would greatly improve the analysis, as these are areas that have attracted less attention from researchers.

[9] ‘Damage functions show the susceptibility of assets at risk to certain inundation characteristics, currently mostly against inundation depth’ (Messner et al., 2007).

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.09.016.

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