

**Destructive events, any size, anywhere:
a tool for rapid assessment of regional and economy-wide effects**

by

**Peter Dixon, Michael Jerie, Dean Mustakinov, Maureen Rimmer, Nicholas Sheard,
Florian Schiffmann and Glyn Wittwer**

Centre of Policy Studies, Victoria University, Melbourne

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Abstract

Destructive events (such as acts of war and natural disasters) of any size can occur at any latitude/longitude. Anticipating direct economic impacts requires regional data at a highly granular level. Estimating broader effects requires modelling encompassing regional and industrial linkages. Informing decision makers requires a tool that can be operated immediately without modelling expertise and possibly in a secure environment. This paper describes a destructive events tool (DET) that meets these requirements. It consists of reduced-form equations that can be implemented rapidly by non-modellers. The reduced-form equations are derived by training a neural network with results from a very large number of computable general equilibrium simulations. The simulations draw on data for small rectangular areas (less than 1 sq km) to provide shocks for destructive events of different sizes in different locations. As an illustrative application we focus on Poland. Our methods could be applied for most countries.

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1. Introduction

This paper describes a destructive events tool (DET) created for decision-makers seeking a capacity to assess at *short notice, in a secure environment*, the likely *regional and national economic effects* of an adverse event with any given destruction/death/evacuation characteristics occurring at *any location* in a country. The events that could be analyzed with the DET include an act of war, a terrorist attack, a natural disaster or a major industrial accident.

We created the DET in three stages.

First, we had to deal with the “any location” requirement. To do this we needed to assemble data for the country of interest showing economic activity and population in regions much smaller than are usually identified in economic models. This is because the effects of a destructive event in one location may be quite different from those of a similar event in a close-by location, depending on differences in economic activity in the two locations.

In the example given in this paper the country is Poland. The choice of Poland was a matter of convenience. We had available a detailed database for Europe and experience with Polish data. We used a grid to divide Poland into 600,000 small rectangular areas (SRAs), each approximately 0.5 sq kilometres. For each SRA we estimated population, and output and employment by industry.

The second stage was to convert destruction in given SRAs into broader *regional and national economic effects*. To do this we used a multi-regional computable general equilibrium (CGE) model. In the Poland model, there are 29 sub-national regions. The input to this CGE model is shocks at the 29-region level calculated by aggregating damage across component SRAs. The focus of our DET is disruption, how the economy can operate in the first three months after the destructive event. Consequently, the CGE model underlying the DET is set up for short-run simulations and ignores the effects of restoration. Using a different setup for the CGE model, our methodology could be generalized to embrace longer-term horizons and restoration.

The final stage was to meet the “*short notice, in a secure environment*” requirement. Simply supplying the CGE model and the SRA database isn’t adequate. Running CGE models requires skills that are not widely available in decision-making groups. While such groups can go to outside providers of CGE services, this is not compatible with quick turnaround and confidentiality. To overcome these difficulties, we use a neural network (NN) technique to

provide equations that approximate the reduced form of the CGE model. The equations can be used quickly by people with generally available computer skills but no CGE experience.

Figure 1.1 is a stylized version of the Poland DET. The shaded boxes show inputs and outputs. The other boxes refer to the internal workings of the DET. Box 1 shows that a user of the DET is required to specify the central location of the event, and areas of total destruction, evacuation and shutdown. These areas can be specified as circles or other shapes usually around the central location.¹ The areas normally embrace several SRAs. The DET program then accesses the entire SRA database and calculates deaths, evacuations and direct loss of capital by industry in the 29 sub-national Polish regions (Box 2). The information from Box 2 is used by the DET program as input to the Neural Network (Box 3) which mimics the CGE model. Notice that the user of the DET is not required to run the CGE model, it is not part of the DET. The Neural Network produces the DET output (Box 4) as an array of results for sub-national and national economic variables.

Sections 2 to 4 show how the DET for Poland was created. Section 2 describes the formation of the SRA database for Poland. Section 3 describes the multi-regional CGE model and how it accepts shocks generated by aggregation from the SRAs. Section 4 and the Appendix explain the creation of the NN approximation to the reduced form of the CGE model.

Concluding remarks are in section 5. There we discuss potential improvements and extensions of the DET, policy uses, and the feasibility of building DETs for countries other than Poland.

Before going to the main part of the paper, we give a summary of earlier efforts in building destructive events tools and contrasts with our effort.

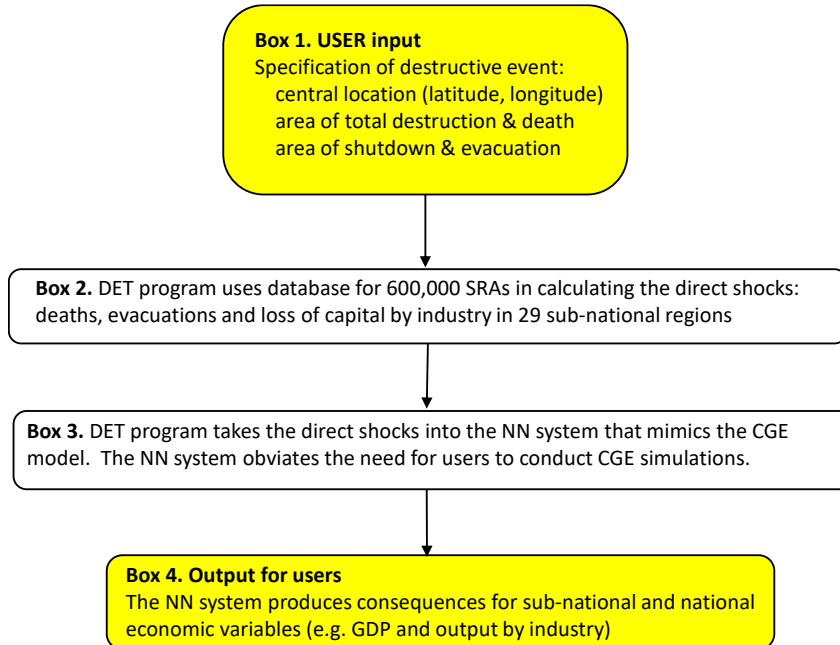
1.1. Destructive events tools: previous studies

To start, we distinguish between the literature on modelling the economic effects of disasters and that on creation of destructive events tools. Okuyama (2022) provides a comprehensive review of the economics literature on modelling disasters. Most of the applied papers he describes can be placed in one of two categories: (a) in-depth analyses of actual disasters and (b) projections of the effects of a relatively limited range of hypothetical disasters. Studies that fit into category (a) include: Okuyama (2015) on the 1995 Kobe earthquake; Basker and Miranda (2018) on Hurricane Katrina; and Walmsley *et al.* (2023) on COVID-19. Category (b) studies include: Colon *et al.* (2021) on flood disruptions of the road network in Tanzania; Giesecke *et al.* (2012) on a dirty bomb attack in Los Angeles; and Wei *et al.* (2022) on disruption of ports in Los Angeles. Inoue and Todo (2019) straddle both categories with an analysis of the 2011 Great Eastern Japan earthquake together with analysis of the predicted Nankai earthquake.

With a DET, the primary aim is to create a tool that can be used independently of its creators to provide a quick aid to decision making in response to a broad range of potential adverse events. Okuyama cites just a few papers that qualify as descriptions of DETs. Here we

¹ Shutdown areas may also include discrete areas if, for example, the loss of a power plant necessitates shutdowns in areas removed from the central location.

Figure 1.1. Stylized representation of the DET for Poland



review two early DET papers. In section 4, we mention three further DET studies which will be more easily understood in that context.

The pioneering DET is Hazus for the U.S. This is a modelling software program that provides standardized tools and data for estimating risk from natural disasters. The backbone of Hazus is a highly detailed building inventory database down to the census block level. The database is constructed using census data, LiDAR measurements, NSI 2022 (USACE), and many more, see FEMA (2022). On top of this database, there are four disaster modelling tools for predicting the impact of earthquakes, hurricanes, floods and tsunamis. The outputs of these modelling tools include: damage estimates to existing structures; repair and rebuild costs; number of affected households; and estimates of business interruption costs.

Hazus presents a bottom-up approach using large amounts of highly detailed data to generate direct damage estimates. These are important in risk/impact assessment, and for emergency services (direct aid) as well as insurance companies. The emphasis in Hazus is on obtaining accurate impact effects, although the tool also contains economic modelling for translating impact effects into regional and national effects, see Brookshire *et al.* (1997).

The tool presented in this study does not have the same inbuilt data detail as Hazus. It uses a top-down approach, disaggregating national and regional economic data and distributing it across SRAs. In this way, it ensures consistency with national and regional input-output data. The results of the presented tool are not the small region impacts but the national and regional impacts of the interruptions and losses caused by disasters. In this sense, our DET is complementary to Hazus.

Yamano *et al.* (2007) present a DET for Japan which is like ours in important ways. It uses data on industrial activity and population in small directly affected districts to accurately estimate the impacts of a destructive event. It then translates these impacts into shocks to a larger region identified in an economy-wide, multi-regional model.

There are three points of contrast between the DET presented here and those of Hazus and Yamano *et al.* First, neither of these earlier DETs contain reduced form representations to facilitate independent use. Second, both Hazus and Yamano *et al.* require data that are not readily available for many countries. We present a data-generating methodology for SRAs that is applicable to most countries. Nevertheless, where data are available of the type used in Hazus and Yamano *et al.*, they could be used in our framework. A final point of contrast between our DET and the earlier tools is our use of CGE modelling. Hazus and Yamano *et al.* use input-output (IO) models.

Okuyama (2022) compares the applicability of IO and CGE models in analysis of destructive events. The main problems with IO modelling are the rigidity of the technology specifications and the lack of supply-side restrictions. Okuyama describes various fixes that have been used to overcome these limitations. Fixes are also required for CGE models to enhance their applicability for analysis of destructive events. In this paper we describe non-standard treatments in our CGE model of capital, exports and population movements. For us, the CGE framework is the more natural for disaster analysis. It incorporates resilience tactics such as: substitution between inputs; use of international or regional imports to replace unavailable local commodities; use of excess capacity to counter shortages; and relocation of businesses, see Dormady *et al.* (2022).

Okuyama (2022, p. 31) concludes that “CGE models are considered ideal modelling frameworks for disaster impact analysis ...”. Despite this, he points out that IO models have been the most popular framework for disaster impact analysis because of their simplicity. By equipping our DET with an NN reduced form, we hope to improve the accessibility of CGE modelling for people concerned with destructive events.

2. Compiling data on economic activity in small rectangular areas of Poland

EuroStat data gives detailed estimates of population and employment by industry for Poland divided into 73 regions (NUTS3 regions), see Figure 2.1. In creating the DET for Poland, we distributed the NUTS3 data to SRAs using Open Street Maps and the Global Power Plant Database. In explaining how the distribution was done, we focus on NUTS3 region PL633. This is centred on downtown Gdansk and is shown in Figure 2.1 as Trójmiejski.

Table 2.1 gives statistics for PL633 and Rest of Poland deduced from EuroStat. PL633 accounts for 3.44 per cent of Poland’s GDP (sum over value added for each industry) and 1.95 per cent of Poland’s population. At the industry level, PL633 specializes in Communications (5.31 per cent of Poland’s Communications output), Manufactures (4.75 per cent) and Finance (4.42 per cent). Very little of Poland’s output of primary industries (agriculture and mining) is located in PL633.

In the rest of this section, we define the SRAs. Then we describe the data we used from Open Street Maps and the Global Power Plant Database. Finally, we show how we used these data to distribute NUTS3 data to the SRAs.

Figure 2.1. The NUTS3 regions of Poland highlighting region PL633 (Trójmiejski, downtown Gdansk)

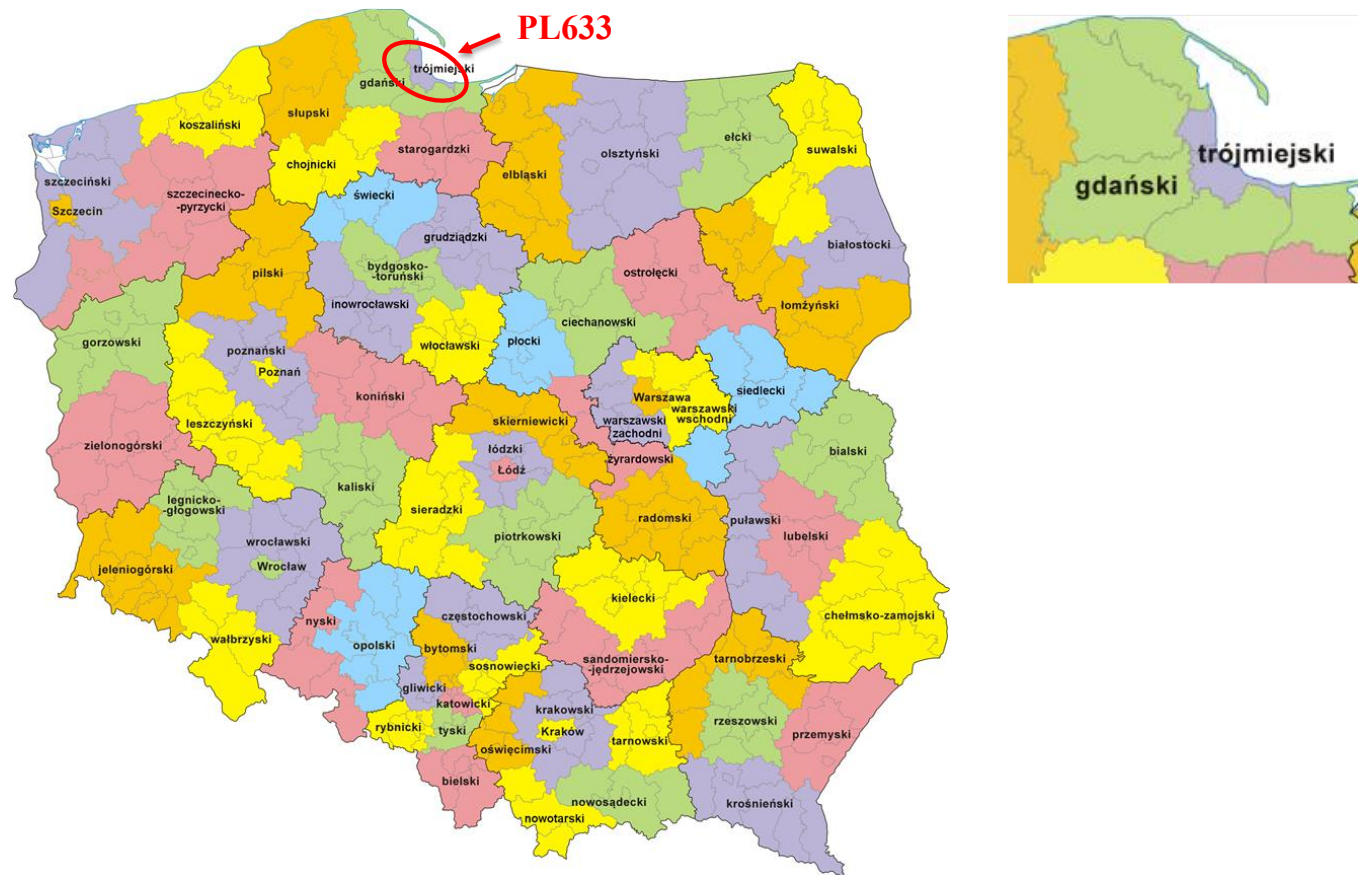


Table 2.1. Population and value-added by industry in PL633 and the Rest of Poland, 2017

	PL633	Rest of Poland	PL633 as percent of Poland
Population	747288	37532025	1.95
<i>Value added (returns to primary factors, \$US million)</i>			
1 Other Ag For Fish	51	9835	0.52
2 Raw Fruit Veg	12	2525	0.47
3 Gas	0	59	0.69
4 Mining	81	8602	0.93
5 Manufactures	4212	84387	4.75
6 Elec Coal	13	1714	0.77
7 Elec Other	6	601	1.04
8 Elec Hydro	4	482	0.90
9 Elec Dist	164	5995	2.66
10 Other Utilities	104	3852	2.63
11 BusSrv & Construct	2994	87156	3.32
12 Trade W'sale & Retail;	1680	58115	2.81
13 Accom & Food Serv	454	10295	4.22
14 Land Transport	418	11049	3.64
15 Water Trnsport	20	514	3.76
16 Air Transport	32	913	3.35
17 Communications	931	16596	5.31
18 Finance	634	13717	4.42
19 Recreat & Personal Serv	317	10345	2.98
20 PubAdm & Def	708	23888	2.88
21 Education	531	18225	2.83
22 HealthSocServ	731	24042	2.95
23 Services of Dwelling	430	14431	2.89
Total	14528	407338	3.44

Defining small rectangular areas (SRAs)

Figure 2.2 indicates the partition of PL633 into the SRAs for which we estimate population, employment and industrial activity. PL633 contains 829 of Poland's 600,000 SRAs.

The north and south boundaries of the SRAs lie along latitude lines separated by 0.00833 degrees (30 arc seconds). The east and west boundaries lie along longitude lines separated by 0.00833 degrees.

Figure 2.3 is an example of an SRA. This particular SRA is labelled PL633a337 in our programs and is highlighted in pink in Figure 2.2. As illustrated in Figure 2.3, the east and west boundaries of PL633a337 are 0.9253 km in length. This length applies to the east and west boundaries of all the SRAs. Given the way latitudes and longitudes are defined, the curvature of the earth means that the length of the north boundary of a Polish SRA is a few centimetres less than that of the south boundary, see Figure 2.3.

We aligned the latitude-longitude grid for the SRAs to facilitate the use of the worldwide LandScan population data, which is on a 30 arc-second grid with the Equator and Prime Meridian (Greenwich) falling half way between neighbouring points. However, for Poland,

Figure 2.2. PL633 partitioned into 829 small rectangular areas

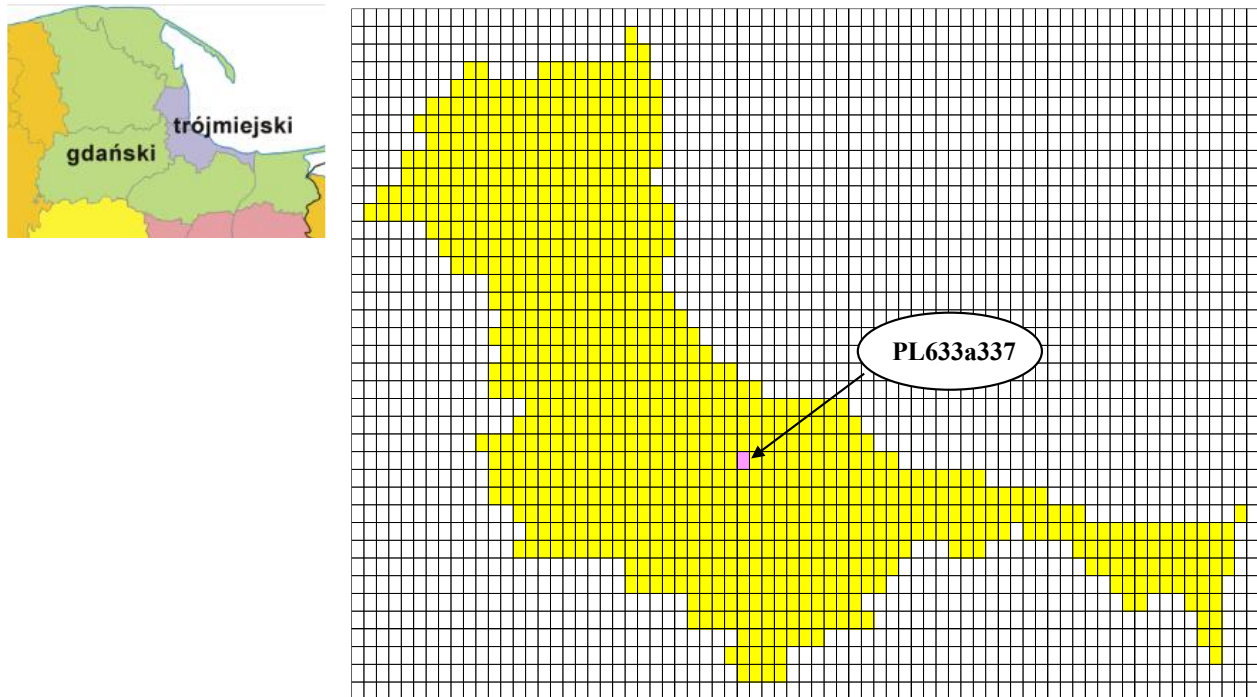
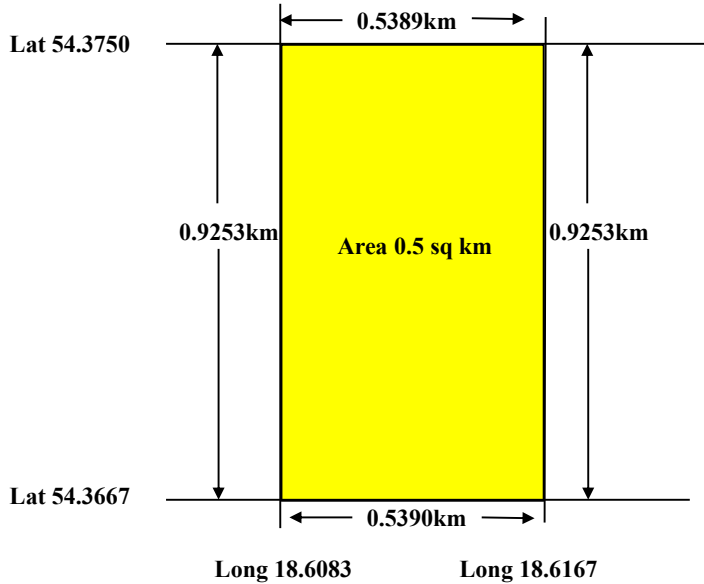


Figure 2.3. Small rectangular area (SRA) PL633a337.
Centroid: Lat 54.3708; Long 18.6125



we used population data from the Eurostat Joint Research Centre (JRC) rather than LandScan. The Eurostat JRC data are assembled from highly disaggregated official data. We converted the Eurostat population data to the LandScan grid by interpolation.

Using Open Street Maps (OSM) to identify characteristics of the SRAs

From OSM we compiled data for each of the 829 SRAs in PL633. The OSM data for a sample of 9 SRAs are in rows 5 to 74 of Table 2.2.

Rows 1 and 2 give the latitude and longitude of the centroid for each SRA. These coordinates are from NASA.

Row 3 gives the land area in sq kms, also from NASA. These areas exclude lakes and sea. Consequently, some SRAs (e.g. PL633a473, column 6 in Table 2.2) have a land area noticeably less than 0.5 sq km.

Row 4 gives resident population, derived from the Eurostat Joint Research Centre.

Rows 5 to 22 show land use shares in each SRA. We derived these data by evaluating the OSM land use characteristic at 100 points within each SRA and calculating the shares of the points with the various land-use characteristics. Following this method, we find that PL633a544 is predominantly forest and nature reserve. PL633a380 is predominantly industrial and PL633a514 is predominantly residential. These findings can be checked using Google Maps (Figures 2.4 to 2.6).

Rows 23 to 28 in Table 2.2 refer to transport infrastructure. OSM gives the latitude and longitude coordinates of railway stations, railway halts, bus stations, etc. In some cases, the location is identified as a single point. In these cases, we assigned the infrastructure to the

Table 2.2. Characteristics of SRAs in PL633 deduced mainly from Open Street Maps (OSM)

	Selected SRAs	PL633a247	PL633a323	PL633a337	PL633a338	PL633a380	PL633a473	PL633a493	PL633a514	PL633a544
	Characteristic	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	latitude at centroid	54.354172	54.370831	54.370831	54.370831	54.379169	54.404171	54.412498	54.420841	54.4375
2	longitude at centroid	18.637501	18.495831	18.612499	18.620831	18.637501	18.6625	18.5875	18.57917	18.52083
3	land area	0.50	0.50	0.50	0.50	0.50	0.44	0.50	0.50	0.50
4	population	1491	109	2439	2040	1279	1330	4952	10396	1
5	Lforest	0.000	0.284	0.200	0.283	0.000	0.088	0.013	0.012	0.470
6	Lpark	0.618	0.000	0.029	0.304	0.000	0.088	0.013	0.085	0.000
7	Lresidential	0.200	0.027	0.671	0.261	0.015	0.333	0.627	0.732	0.000
8	Lindustrial	0.000	0.014	0.000	0.000	0.971	0.316	0.013	0.000	0.000
9	Lcemetery	0.055	0.000	0.000	0.043	0.000	0.000	0.000	0.000	0.000
10	Lallotments	0.000	0.000	0.014	0.022	0.000	0.000	0.000	0.000	0.000
11	Lmeadow	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	Lcommercial	0.018	0.000	0.000	0.022	0.000	0.000	0.013	0.000	0.000
13	LnatureResrv	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.500
14	LrecreatGrnd	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
15	Lretail	0.000	0.000	0.000	0.000	0.000	0.000	0.093	0.024	0.000
16	Lmilitary	0.000	0.000	0.000	0.000	0.000	0.088	0.000	0.000	0.000
17	Lorchard	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
18	Lscrub	0.091	0.041	0.029	0.000	0.000	0.070	0.000	0.000	0.030
19	Lgrass	0.018	0.568	0.057	0.065	0.015	0.018	0.227	0.146	0.000
20	Lheath	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
21	Lfarmyard	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
22	Lfarmland	0.000	0.068	0.000	0.000	0.000	0.000	0.000	0.000	0.000
23	TrailwayStat	0	0	0	0	0	0	0	0	0
24	TrailwayHalt	0	0	0	0	0	0	0	0	0
25	Tbus station	0	0	0	0	0	0	0	0	0
26	Tairport	0	1	0	0	0	0	0	0	0
27	Thelipad	1	1	0	0	0	0	0	0	0
28	TferryTrmnl	0	0	0	0	0	1	0	0	0

Table 2.2 continues ...

... Table 2.2 continued

	Selected SRAs	PL633a247	PL633a323	PL633a337	PL633a338	PL633a380	PL633a473	PL633a493	PL633a514	PL633a544
	Characteristic	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
29	police station	1	0	0	0	0	1	0	0	0
30	fire station	0	0	0	0	0	0	0	0	0
31	post office	1	0	1	0	0	0	1	1	0
32	library	0	0	0	0	0	0	0	0	0
33	town hall	1	0	0	0	0	0	0	0	0
34	courthouse	1	0	0	0	0	0	0	0	0
35	prison	1	0	0	0	0	0	0	0	0
36	embassy	0	0	0	1	0	0	0	0	0
37	nursing home	0	0	0	0	0	0	0	0	0
38	market place	0	0	0	0	0	0	0	0	0
39	university	0	0	1	1	0	0	0	0	0
40	school	0	0	1	1	0	1	1	1	0
41	kindergarten	0	0	1	0	0	0	1	1	0
42	college	0	0	0	0	0	0	0	0	0
43	publicBuildg	0	0	0	0	0	0	0	0	0
44	pharmacy	1	0	1	0	0	1	1	1	0
45	hospital	1	0	0	1	0	0	0	0	0
46	clinic	1	0	0	1	0	0	0	1	0
47	doctors	1	0	0	0	0	0	1	1	0
48	dentist	1	0	1	0	0	0	1	1	0
49	theatre	0	0	0	1	0	0	0	0	0
50	cinema	0	0	0	0	0	0	0	0	0
51	restaurant	1	0	1	1	0	0	1	1	0
52	fast food	0	0	1	1	0	0	1	1	0
53	cafe	0	0	0	1	0	0	1	0	0
54	pub	0	0	0	0	0	0	1	0	0
55	bar	0	0	1	0	1	0	0	0	0
56	food court	0	0	0	0	0	0	0	0	0
57	biergarten	0	0	0	0	0	0	0	0	0
58	hotel	1	0	0	0	0	0	0	0	0
59	motel	0	0	0	0	0	0	0	0	0
60	guesthouse	0	0	1	0	0	0	0	0	0
61	hostel	0	0	0	0	0	0	0	0	0

Table 2.2 continues ...

... Table 2.2 continued

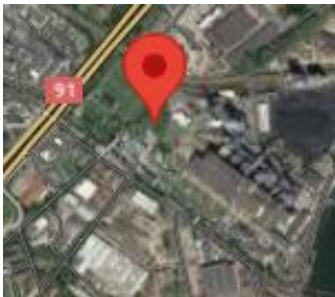
	Selected SRAs	PL633a247	PL633a323	PL633a337	PL633a338	PL633a380	PL633a473	PL633a493	PL633a514	PL633a544
	Characteristic	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
62	chalet	0	0	0	0	0	0	0	0	0
63	supermarket	0	0	0	0	0	1	1	1	0
64	departmtStor	0	0	0	0	0	0	0	0	0
65	bank	1	0	0	0	0	0	1	1	0
66	theme park	0	0	0	0	0	0	0	0	0
67	tower	1	0	0	0	0	1	0	0	0
68	comms tower	0	0	0	0	0	0	1	0	0
69	water tower	0	0	0	1	0	0	0	0	0
70	lighthouse	0	0	0	0	0	1	0	0	0
71	wasteWatPlt	0	0	0	0	0	0	0	0	0
72	water well	0	0	0	0	0	0	0	0	0
73	water mill	0	0	0	0	0	0	0	0	0
74	water works	0	0	0	0	0	0	0	0	0

**Figure 2.4. Google Maps satellite and street view centred on PL633a544
(predominantly forestry and nature reserve)**



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**Figure 2.5. Google Maps satellite and street view centred on PL633a380
(predominantly industrial)**



**Figure 2.6. Google Maps satellite and street view centred on PL633a514
(predominantly residential)**

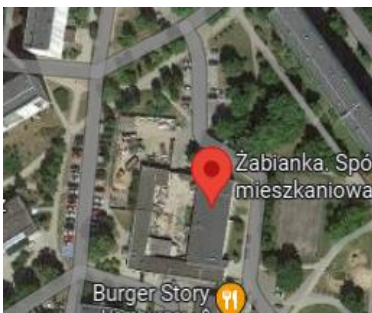


Figure 2.7. Google Maps satellite view centred on PL644a323 (shows airport)

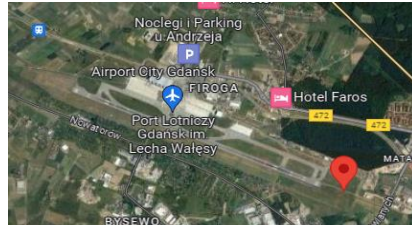


Figure 2.8. Google Maps satellite and street view centred on PL633a473 (shows ferry terminal)



SRA in which the identifying point is located. In the case of large infrastructure items, e.g. airports, OSM gives a set of coordinates on the periphery of the item. We assumed that the boundary of the item is formed by the polygon joining the peripheral coordinates. We assigned the item to each of the SRAs whose area intersects with the polygon. Consequently, large infrastructure items can be assigned to several SRAs. For example, the Gdansk airport is assigned to 13 SRAs.

Following this procedure, we formed a 1,0 score for each transport infrastructure type in each SRA: 1 if the type is present and 0 otherwise. Glancing at Table 2.2, we see that none of the 9 featured SRAs has a railway station, a railway halt, or a bus station. PL633a323 includes part of the airport (confirmed in Figure 2.7) and a helipad. There is also a helipad in PL633a247. PL633a473 has a ferry terminal (confirmed in Figure 2.8).

The 1s and 0s in the remaining rows of Table 2.2 identify the presence or absence in an SRA of a wide variety of features including, police stations, fire stations, several types of medical facilities, several types of education facilities, retail outlets, entertainments, accommodation and utilities such as water treatment.

Using the Global Power Plant Database to identify power plants in PL633 by SRA location

The Global Power Plant Database provided by the World Resources Institute (<https://github.com/wri/global-power-plant-database>) gives the location, fuel type and capacity of electricity generation plants in most parts of the world. Using these data, we

found that power plants are located in 6 of the SRAs in PL633. This can be checked using google maps (see for example Figure 2.9). As can be calculated from Table 2.3, 87 per cent of the power generation in PL633 is provided by the coal-fired power station located in PL633a380 (see Figure 2.9).

Estimating SRA shares in PL633's output in each industry

For each of the 23 industries listed in Table 2.1, we allocated activity from the PL633 level to the SRA level by estimating values for $FRACTION(r,j)$ in the formula

$$VA(r,j) = FRACTION(r,j) * VAPL633(j) \quad , r = 1, \dots, 829, j = 1, \dots, 23 \quad (2.1)$$

where

$VA(r,j)$ is value added in SRA r and industry j ;

$VAPL633(j)$ is value added for industry j in NUTS3 region PL633; and

$FRACTION(r,j)$ is the fraction of PL633's value added in industry j that we allocate to the r^{th} SRA. Our data at the NUTS3 level divides value added for industry j into returns to labor, capital and land. We use the same allocating fractions for each of the three primary factors, and for the industry's output. Table 2.4 indicates the basis on which we estimated the allocating fractions.

For power generation, industries 6 – 8, we set $FRACTION(r,j)$ by using the data in Table 2.3. We allocated 100 per cent of PL633's Coal electricity (industry 6) to PL633a380. For Hydro electricity (industry 8), we allocated 38.38 per cent to PL633a54, 38.38 per cent to PL633a85 and 23.25 per cent to PL633a20. Other electricity (industry 7) consists of all generation except Coal and Hydro. In PL633 the only power plants in the Other category are Wind and Solar plants, both located in PL633a154. Consequently, we allocated 100 per cent of PL633's Other electricity to PL633a154.

For Services of dwellings (industry 23), we allocated activity to the SRA's according to the SRA population data that we derived from the Eurostat Joint Research Centre. If one SRA has a population twice that of another, then we assume that the annual rental value of the housing stock in the first SRA is twice that of the second SRA. We also used population as the allocating factor for Electricity distribution (industry 9), Gas (industry 3) and Mining (industry 4). This is reasonable for Electricity distribution and possibly Gas which is mainly devoted to distribution: higher population generally means higher use of electricity and gas. For Mining, population is a default allocating factor. In PL633, Mining is a small industry (Table 2.1).

PL633's activity in Other agriculture, forestry and fishing (industry 1) is allocated to SRAs in proportion to their share of PL633's farmland (row 22, Table 2.2). For Raw fruit and veg (industry 2) we use Orchard land (row 17, Table 2.2) as the allocating factor. For Manufactures (industry 5) we use industrial land (row 8, Table 2.2). For Business services & construction (industry 11) we use commercial land (row 12, Table 2.2).

Figure 2.9. Google Maps satellite view centred on PL644a380 (shows coal-fired power station)



Table 2.3. Power plants in PL633: capacity in Gw-hrs, Data for 2020

Power plant	Bielkowo	Ecgdask	Ffdeltaprze	Fwbystra	Apino	Straszyn	Total
SRA	PL633a54	PL633a380	PL633a154	PL633a154	PL633a85	PL633a20	
1 coal	0	901.38	0	0	0	0	901.38
2 gas	0	0	0	0	0	0	0
3 geothermal	0	0	0	0	0	0	0
4 hydro	18.77	0	0	0	18.77	11.37	48.91
5 nuclear	0	0	0	0	0	0	0
6 oil	0	0	0	0	0	0	0
7 other	0	0	0	0	0	0	0
8 solar	0	0	2.89	0	0	0	2.89
9 waste	0	0	0	0	0	0	0
10 wind	0	0	0	78.04	0	0	78.04
Total	18.77	901.38	2.89	78.04	18.77	11.37	1031.22

Other industries (industries 10 and 12-22)

For the remaining industries, the allocating fractions depend on the OSM data and the 1,0 scores in rows 23 to 74 in Table 2.2. For these industries we calculated the allocating fractions according to

$$\text{FRACTION}(r, j) = \frac{\sum_{c \in \text{OSM}(j)} \text{ID}(r, c) * \text{WGT}(c, r, j)}{\sum_{rr=1}^{829} \left[\sum_{c \in \text{OSM}(j)} \text{ID}(rr, c) * \text{WGT}(c, rr, j) \right]} \quad (2.2)$$

In (2.2),

OSM(j) is the subset of the characteristics defined in rows 23 to 74 in Table 2.2 that we judge to be evidence of activity in industry j. For example, as indicated in Table 2.4, when j is Education (industry 21) then OSM(j) is university (row 39, Table 2.2), school (row 40), kindergarten (row 41) and college (row 42).

ID(r,c) is the 1,0 score for characteristic c in SRA r. For example, in Table 2.2, ID(r,c) is 1 for University in PL633a337 and PL633a338 (row 39, Table 2.2). This indicates the presence of a university in these two SRAs.

$WGT(c,r,j)$ is the weight we attach to characteristic c in determining the level of activity in industry j in SRA r associated with characteristic c .

In forming the weights, we started by setting them all at 1. Then we made two sets of revisions. First, we focused on the problem that there can be several characteristics present in an SRA contributing to activity in industry j . This led us to make judgements about levels of contributions of different characteristics. For example, for the Education industry ($j=21$), the weights we assigned were 3 for the presence of a university, 1 for a school, 0.2 for a kindergarten and 2 for a college.

The first set of revisions generated some implausible results for SRAs in low-population areas. It became apparent that we needed to introduce the idea that police stations, courthouses, public buildings, clinics, hotels, supermarkets, department stores, and banks (rows 29, 34, 43, 46, 58, 63, 64 and 65, Table 2.2) are likely to be bigger when they are located in high-population areas than when they are located in low-population areas. After some experimenting, we made a second set of revisions to the weights for these characteristics. For each r we multiplied their weights by a number between 1.0 and 4.4: 1.0 (that is no adjustment) in SRAs for which the population within a radius of 3 kms of the centroid of the SRA is less than 4,000, rising to 4.4 for the SRA with the maximum 3-km population, which in PL633 happens to be 133,947.

Table 2.4. Ingredients in the allocation of industry activities to SRAs

Industries	Characteristic in the calculation of $FRACTION(r,j)$
1 Other Ag For Fish	Lfarmland
2 Raw Fruit Veg	Lorchard
3 Gas	Population
4 Mining	Population
5 Manufactures	Lindustrial
6 Elec Coal	Data in Table 2.3
7 Elec Other	Data in Table 2.3
8 Elec Hydro	Data in Table 2.3
9 Elec Dist	Population
10 Other Utilities	WasteWaterPlt, Water tower, Water well, Water mil, Water works
11 BusSrv & Construct	Lcommercial,
12 Trade W'sale & Retail	Market place, Pharmacy, Supermarket, Department store
13 Accom & Food Serv	Restaurant, Fast food, Café, Pub, Bar, Food court, Biergarten, Hotel, Motel, Guesthouse, Hostel, Chalet
14 Land Transport	TrailwayStat, TrailwayHalt, Tbus station
15 Water Trnsport	Ferry terminal, Lighthouse
16 Air Transport	Tairport, Thelipad
17 Communication	Post office, Tower, Communications tower
18 Finance	Bank
19 Recreat & Personal Serv	Library, Town hall, Public building, Theatre, Cinema, Theme park
20 PubAdm & Def	Police, Fire station, Courthouse, Prison, Embassy
21 Education	University, School, Kindergarten, College
22 HealthSocServ	Hospital, Clinics, Doctors, Dentist, Nursing home
23 Services of Dwellings	Population

It matters where an event happens: estimating the shares in PL633's economy located in user specified zones

In constructing DET, we envisage a destructive event that is centred at a particular location and can cause total destruction in a surrounding area and cessation of economic activities and evacuation in a larger area. This is illustrated in Figure 2.10 where destructive events are centred in four SRAs: PL633a337, PL633a380, PL633a514, and PL633a544. In these examples, the destruction zones are the inner circles with radius 1 km and the evacuation zones are the doughnuts between the inner and outer circles. The outer circles have radius 3 km.

Users of DET can choose other shapes for the destruction and evacuation zones, and other sizes. But whatever the choices, the DET programs calculate pre-event economic activity in the zones by aggregating across SRAs. Where the border of a zone passes through an SRA, the program calculates the fraction of the SRA's activity that should be included in the relevant zone. Where there are multiple destructive events and overlapping zones, the program avoids double counting.

Table 2.5 shows zone results for potential events at the locations marked in Figure 2.10. The first row in Table 2.5 shows resident populations in the 1 km and 3 km circles. The second row expresses these population numbers as percentages of PL633's population (which is 747,288). The remaining rows show percentages of PL633's capital by industry located in the 1 km and 3 km circles.

In a destructive event scenario centred in one of these SRAs, we might treat the 1-km population as immediate fatalities and the difference between the 3-km and 1-km populations as evacuees. We might assume that all the capital in the 1-km circle is destroyed and the capital in the evacuation zone is left idle.

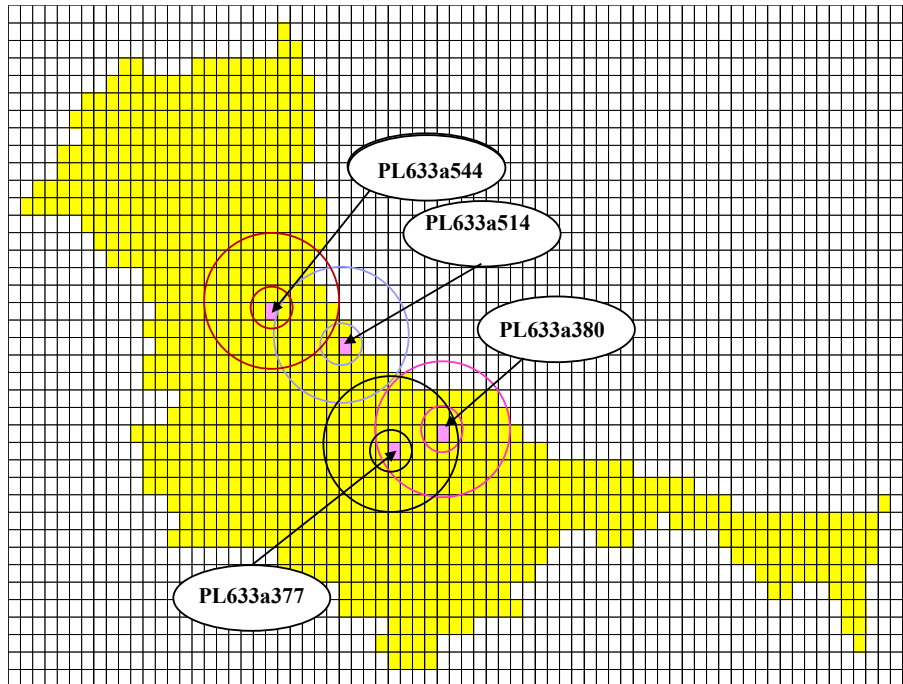
What Table 2.5 brings out is the importance of pinpointing the location of a destructive event in establishing its likely impact.

For a destructive event centred on PL633a337 (downtown Gdansk), the fatality zone contains 8,639 people, and the evacuation zone contains 110,842 people (= 119,481 - 8,639). Industries in the 3-km circle that would be disproportionately disrupted by an event in PL633a337 are Coal electricity generation, Recreation & personal services, Education and Other utilities.

By contrast, the fatality zone for an event in PL633a544 (predominately a forest and nature reserve) contains only 64 people, and the evacuation zone, which embraces suburban areas adjacent to the forest and nature reserve, contains 10,464 (= 10,528 - 64). In the 3-km zone for PL633a544, the entries for most industries are relatively small.

In the 1-km fatality zone for PL633a514 there are 16,818 people. This is a residential area. The number in the 3-km zone is 96,440, requiring 79,622 evacuations. Although PL633a514 is predominantly residential, a destructive event centred on this SRA would cause noticeable capital losses across most industries. Exceptions are the power generation industries. There is no generation capacity within 3-km of the PL633a514 centroid.

Figure 2.10. Four locations for destructive event and areas of radius 1 km and 3 km



In the 1-km fatality zone for PL633a380, there are 7,414 people, and in the 3-km zone there are 88,629 people (requiring 81,215 evacuations). PL633a380 is an industrial area with both manufacturing and services provision. A destructive event centred on PL633a380 would knock out PL633's coal-fired electricity generation (the bulk of PL633's generation capacity, see Table 2.3).

3. The CGE model: converting destruction scenarios into regional and national economic effects

For creating the Polish DET, we need an economic model that accepts shocks representing capital destruction or idling by Polish region and industry, and deaths and evacuations by region. For example, we wanted to be able to apply shocks such as those indicated in Table 2.5 to the relevant region of Poland (in this case PL633) and to work out economic implications for this region and other Polish regions. To meet this requirement, we constructed Euro-TERM-PL. As with all TERM² models, this is a multi-regional computable general equilibrium (CGE) model.

² The Enormous Regional Model. The TERM methodology was pioneered by Horridge *et al* (2005). In recent years, it has been developed and extended by Glyn Wittwer and others at the Centre of Policy Studies, see for example Wittwer (2017 and 2024) and Wittwer and Horridge (2018).

Table 2.5. Information for calculating population and capital effects of destructive events in selected SRAs in PL633

<i>Ground zero Radius around ground zero</i>	PL633a337		PL633a380		PL633a514		PL633a544	
	1 km	3 km	1 km	3 km	1 km	3 km	1 km	3 km
Population	8639	119481	7414	88629	16818	96440	64	10528
% of PL633's population	1.16	15.99	0.99	11.86	2.25	12.91	0.01	1.41
% of PL633's capital								
1 OthAgForFish	0.00	0.00	0.00	0.00	0.00	4.71	0.00	1.18
2 RawFruitVeg	0.00	0.00	0.00	0.00	0.00	4.71	0.00	1.18
3 Gas	1.16	15.99	0.99	11.86	2.25	12.91	0.01	1.41
4 Mining	1.16	15.99	0.99	11.86	2.25	12.91	0.01	1.41
5 Manufactures	0.03	6.89	2.52	16.86	0.10	1.64	0.00	0.17
6 ElecCoal	0.00	95.00	95.00	95.00	0.00	0.00	0.00	0.00
7 ElecOther	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8 ElecHydro	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9 ElecDist	1.16	15.99	0.99	11.86	2.25	12.91	0.01	1.41
10 OthUtilities	1.41	21.36	0.00	13.15	0.94	10.80	0.00	0.47
11 BusSrv	0.85	20.40	0.00	4.25	0.00	2.55	0.00	8.50
12 TradeWR	0.00	10.03	0.00	5.64	1.25	19.75	0.00	0.63
13 AccomFood	0.22	9.87	0.39	8.31	0.70	7.35	0.04	0.87
14 LandTransprt	0.00	12.94	1.10	12.58	0.85	3.54	0.00	0.24
15 WaterTrnsprt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16 AirTransport	0.00	0.48	0.00	0.24	0.00	0.00	0.00	0.00
17 Communicatn	1.16	15.99	0.99	11.86	2.25	12.91	0.01	1.41
18 Finance	0.00	20.00	0.00	20.00	0.00	20.00	0.00	0.00
19 Recreat&PersonalServ	7.84	33.33	3.92	33.33	0.00	25.49	0.00	5.88
20 PubAdmDefClb	1.89	17.74	0.38	7.55	0.38	4.53	0.00	2.26
21 Education	7.28	23.60	0.56	19.88	2.09	15.70	0.00	2.15
22 HealthSocServ	1.44	19.71	0.21	12.53	0.62	10.88	0.00	1.64
23 OwnerDwelling	1.16	15.99	0.99	11.86	2.25	12.91	0.01	1.41

Section 3.1 describes Euro-TERM-PL focusing on non-standard features. Section 3.2 presents illustrative simulations. These reveal how the model works and are useful in assessing the realism of the results.

3.1. Euro-TERM-PL: description and non-standard features

Euro-TERM-PL identifies Poland (PL) and the Rest of Europe (RoEU). Initially, Poland was split into its 73 NUTS3 regions. In the final version, the regional dimension for Poland was reduced to 29. This made the model more computationally manageable. The loss of regional detail was minor because we chose to aggregate regions in which there was little economic activity. With RoEU treated as a single region, Euro-TERM-PL has 30 regions. The regions are modelled as trading economies with flows of capital and labour between the regions of Poland. For the initial database, trade flows were estimated by a modified gravity formula. In simulations, trade flows react to changes in regional demands and relative prices. Interregional capital flows react to relative rates of return while labour flows react to relative wage rates and employment opportunities.

Our primary interest is short-run disruption. Consequently, the model was set up in short-run comparative-static mode. It produces results that we interpret as showing how different the economy would be three months after an adverse event from the way it would have been without the event. With this short-run focus, interregional flows of capital are strongly muted, and we assume that there has not been enough time for restoration of damaged or idle capital. Apart from evacuations, labour flows are also muted. Longer periods and restoration activities could be accommodated with a modest amount of additional data and a long-run or dynamic setup.³

The standard specifications in TERM models are documented elsewhere, see for example, Wittwer (2017). Documentation specific to Euro-TERM is in Wittwer (2022). Here, we describe assumptions and modifications to the standard specification introduced to facilitate simulations of the short-run effects of destructive events.

Population flows

As a default option, we assume that evacuated people go to regions in the nation outside the regions for which any evacuation takes place and that in each receiving region, the ratio of incoming evacuees to population is the same. Rose and Djavadi (2025) list factors that affect population flows including non-compliance with evacuation orders, or the opposite stemming from unfounded fears. They point out that misspecification of population flows can lead to large errors in the estimation of the effect of adverse events. In applying our DET to analysis of actual events, users can modify the default option as information emerges.

Reallocation of government expenditure

We assume that the government transfers its expenditure out of damaged regions. These are the regions from which evacuations take place. We also assume that the government undertakes expenditures on behalf of evacuees in the regions to which they move. The specifications we use are as follows:

³ CGE modellers adopt different closures (choice of exogenous variables) to achieve short-run, long-run and dynamic setups, see for example, Dixon *et al.* (1982, section 6) and Dixon and Rimmer (2002, ch. 1 & 5).

$$\Delta \text{GOV}(c, d) = - \frac{\text{LOSTPOP}(d)}{\text{POP}(d)} * \text{GOV}(c, d) \quad \text{for all } c \in \text{Com and for all } d \in \text{SEvac} \quad (3.1)$$

$$\begin{aligned} \Delta \text{GOV}(c, r) = & F_G(c) * \left(\sum_{d \in \text{SEvac}} \frac{\text{EVAC}(d)}{\text{POP}(d)} * \text{GOV}(c, d) \right) * \left(\frac{\text{GOV}(c, r)}{\sum_{rr \in \text{SReceive}} \text{GOV}(c, rr)} \right) \\ & + F_H(c) * \left(\sum_{d \in \text{SEvac}} \frac{\text{EVAC}(d)}{\text{POP}(d)} * \text{HOU}(c, d) \right) * \left(\frac{\text{EVACIN}(r)}{\sum_{rr \in \text{SReceive}} \text{EVACIN}(rr)} \right) \\ & - \text{GOV}(c, r) * \text{scalarG} \end{aligned} \quad (3.2)$$

for all $c \in \text{Com}$ and for all $r \in \text{SReceive}$

In (3.1),

SEvac is the set of damaged regions (regions among the 29 in Poland from which evacuations take place);

Com is the set of all commodities;

$\Delta \text{GOV}(c, d)$ is the change in the quantity of commodity c bought by the government in region d , where d belongs to SEvac;

LOSTPOP(d) is the reduction in d 's population due to death and evacuation;

POP(d) is the original population of region d ; and

GOV(c, d) is the original volume of government expenditure on commodity c in d .

In (3.1) we assume that the government reduces its expenditure in damaged region d in line with the proportion of d 's population that is lost.

In (3.2),

SReceive is the set of undamaged regions (regions that receive evacuees);

$\Delta \text{GOV}(c, r)$ is the change in the quantity of commodity c bought by the government in region r , where r belongs to SReceive;

EVAC(d) is the number of people evacuated from region d , so EVAC(d)/POP(d) is the proportion of d 's population that evacuates;

HOU(c, d) is the original quantity of commodity c purchased by households in region d ; and

EVACIN(r) is the number of evacuees that relocate to region r .

For understanding equation (3.2), we can delay discussion of $F_G(c)$, $F_H(c)$ and scalarG . We temporarily assume that they have the values 1, 1 and 0.

With these values, we interpret the first bracketed factor in the first line on the RHS of (3.2) as the quantity of government expenditure on commodity c that is transferred out of damaged regions. Via the second bracketed term, we assume that transferred expenditure goes to receiving regions in proportion to government spending in these regions. At first glance, it

may seem strange to assume that the destinations of reallocated government expenditures are independent of the destinations of the evacuees. We have in mind that the government might provide services to all regions largely by buying inputs to produce public administration, defence, etc in a few regions. When some regions are damaged, the government increases its production of public services in other regions in proportion to the original regional configuration of government expenditures.

We interpret the first bracketed factor in the second line on the RHS of (3.2) as the quantity of household expenditure on commodity c that is transferred out of damaged regions. Via the second bracketed term, we assume that the transferred expenditure goes to receiving regions in proportion to incoming flows of evacuees.

Next, we consider the terms $F_G(c)$ and $F_H(c)$. We can reset these parameters at numbers apart from 1 to introduce changes in the composition of transferred expenditures. In our examples for Poland, we have emphasized expenditure on Health services, Communication, Accommodation & food, Public administration & defence. We have done this by setting $F_G(c) = F_H(c) = 4$ for $c = \text{Health}$ and 2 for the other emphasized commodities. For all other commodities we set these parameters at 0.5.

Finally, we explain the variable scalarG . We use this variable to introduce assumptions concerning the aggregate level of government expenditure. In our examples for Poland, we have allowed the model to find the value of scalarG that leaves aggregate government expenditure for Poland unchanged.

Household consumption

In the evacuating regions, we assume real household consumption adjusts by the same percentage as population. In the other (non-damaged) regions, we assume that incumbent households maintain their baseline levels of consumption. Incoming evacuees are provided for by the government.

Investment

We assume that investment in each region (including RoEU) moves in line with capital stock in use. Consequently, investment collapses in seriously damaged regions. In most other regions, capital in use falls slightly in accordance with the capital supply curve described in the next sub-section and there is a corresponding small fall in investment.

Capital supply curve: allowing for excess capacity

In CGE simulations for the short run, the standard assumption is that the quantity of capital available in each industry is predetermined or exogenous, and that the demand for this capital is brought into equality with the available supply via adjustments in the capital rental rate. However, in simulations concerned with destructive events in which there can be large exogenously imposed changes in the supply of capital and large changes in the demand for capital, we have found that the standard assumption can lead to extreme movements in capital rental rates. The problem is that for some industries the determination of rental rates rests on a knife edge. On the one hand, destruction of capital can be a strong positive force on the rental rate of an industry's capital. On the other hand, evacuation of people can be a strong negative force.

Extreme movements in rental rates can cause computational problems and unrealistic movements in commodity prices with consequent difficulties in simulating effects on regional and international trade.

Under the standard assumption, the short-run supply curve for capital to each industry is vertical, that is supply is unaffected by the rental rate. In Euro-TERM-PL, we soften the movements in rental rates by replacing the vertical supply curves with supply curves that are upward sloping but not vertical, that is supply increases in response to increases in rental rates. We simulate the effects of reductions in the availability of capital as leftward movements in these supply curves.

Our specification of the capital supply curve to industry (j,r) is:

$$\frac{PCAP(j,r)}{PCAP^{base}(j,r)} = L - A * \exp(B/U) + A * \exp\left\{B / \left[U - \frac{XCAP_u(j,r)/XCAP_a(j,r)}{XCAP_u^{base}(j,r)/XCAP_a^{base}(j,r)} \right] \right\} \quad (3.3)$$

where

$PCAP(j,r)$ is the rental price of capital in industry j in region r;

$XCAP_u(j,r)$ is the quantity of capital in use in industry (j,r);

$XCAP_a(j,r)$ is an exogenous shift variable in the supply curve and can be interpreted as the quantity of capital available in industry (j,r);

$XCAP_u^{base}(j,r)$, $XCAP_a^{base}(j,r)$ and $PCAP^{base}(j,r)$ are the initial (pre-destructive event) values of $XCAP_u(j,r)$, $XCAP_a(j,r)$ and $PCAP(j,r)$; and

A, B, L and U are positive parameters.

An underlying story for (3.3) is that there is a capitalist who owns 10 units of capital specific to industry (j,r). This is available capital, $XCAP_a(j,r) = 10$. Under normal conditions the capital owner rents out 80% of its stock to firms in industry (j,r). This would mean that $XCAP_u(j,r) = 8$. On average there are 2 units of capital in stock undergoing servicing or being held to meet surge demands. We assume that the initial situation is normal, implying that $XCAP_u^{base}(j,r)/XCAP_a^{base}(j,r) = 0.8$. If in the post-event situation

$XCAP_u(j,r)/XCAP_a(j,r)$ moves above the normal ratio, we want the simulation to indicate a steep rise in the rental rate $PCAP(j,r)$. If on the other hand $XCAP_u(j,r)/XCAP_a(j,r)$ moves below the normal ratio, then we want a relatively small decline in $PCAP(j,r)$. That is, we want to assume that the capitalist chokes off excess demands by raising rentals but, at least in the short run, the capitalist is reluctant to reduce rentals in response to a decline in demand and is willing to allow significant declines in $XCAP_u(j,r)/XCAP_a(j,r)$. We achieve the required shape for the supply curve through suitable choices for the parameter values.

Looking at (3.3) we see that as $[XCAP_u/XCAP_a]/[XCAP_u^{base}(j,r)/XCAP_a^{base}(j,r)]$ approaches U, PCAP goes to infinity. This tells us that U is an upper bound on the ratio of capital in use to capital in existence relative to the normal ratio. We assume that $U = 1.2$, that is, the use-to-availability ratio can rise no higher than 20 per cent above the normal ratio (e.g. 0.96 compared with 0.8).

Next, we see that if capital in use falls to zero then $PCAP(j,r)/PCAP^{base}(j,r) = L$. This tells us that L is a lower bound on $PCAP$ relative to its initial value. We set L at 0.5. This limits the reductions in capital rentals to 50 per cent.

The steepness of the capital-supply curve is dictated by the value of B . After some trial and error, we set B at 0.1. Now we can determine the value of the last parameter, A , from the initial conditions:

$$1 = 0.5 - A * \exp(0.1/1.2) + A * \exp(0.1/(1.2-1)) \quad (3.4)$$

giving $A = 0.889969$. With all the parameters in place, our choice of B implies that $PCAP$ increases by about 95 per cent relative to its initial value if the use-to-availability ratio for capital moves 10 per cent above normal:

$$1.951876 = 0.5 - 0.889969 * \exp(0.1/1.2) + 0.889969 * \exp(0.1/(1.2-1.1)) \quad (3.5)$$

Figure 3.1 illustrates the supply curve in the initial situation in which $XCAP_a$ equals $XCAP_a^{base}$ and in a situation in which 50 per cent of capital becomes unavailable, leaving $XCAP_a$ equal to $0.5 * XCAP_a^{base}$.

On the initial supply curve, $PCAP$ equals $PCAP^{base}$ when $XCAP_u$ equals $XCAP_u^{base}$, and $PCAP$ rises about 95 per cent above $PCAP^{base}$ when $XCAP_u$ is $1.1 * XCAP_u^{base}$. If available capital is reduced by 50 per cent, then the supply curve moves to the left by 50 per cent. On the new supply curve, $PCAP$ equals $PCAP^{base}$ when $XCAP_u$ equals $0.5 * XCAP_u^{base}$, and $PCAP$ rises about 95 per cent above $PCAP^{base}$ when $XCAP_u$ is $0.55 * XCAP_u^{base}$. On both supply curves, $PCAP$ falls to $0.5 * PCAP^{base}$ when $XCAP_u$ falls to zero.

Preference shifts against products from damaged regions

In Euro-TERM-PL, each region d in Poland chooses the regions from which it sources its requirements for any domestic⁴ commodity (c , dom) via a CES cost-minimizing problem in which units of (c , dom) from different regions are treated as imperfect substitutes. The CES functions for each region include preference variables.

Difficulties in accessing goods from damaged regions or fear that they are contaminated can lead to preference shifts against these goods, see Giesecke *et al.* (2012). Using the preference variables, we assume that all regions in Poland adjust their preferences against all products except electricity from damaged regions (those suffering deaths or positive evacuations).

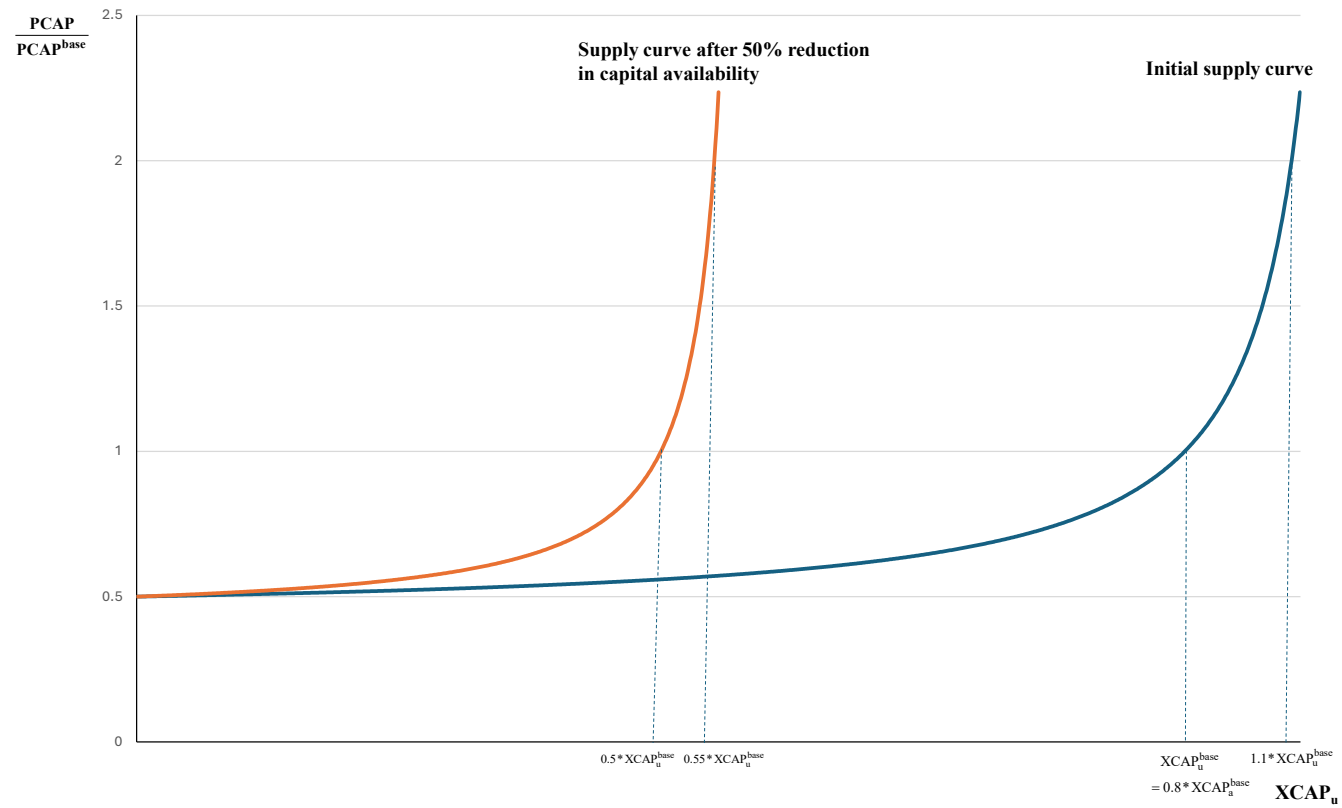
The preference shifts for region d are set according to:

$$\begin{aligned} d_ttrad(c, dom, r, d) &= -EVAC_SH(r) \quad d, r \in \text{Polish regions} \\ &\text{and } c \in \text{COMLELEC} \end{aligned} \quad (3.6)$$

where

⁴ Produced in Poland or RoEU, but not in rest of world.

Figure 3.1. Capital supply curves: initial situation and after 50% reduction in capital availability



COMLELEC is the set of all commodities excluding electricity;

EVAC_SH(r) is the proportion of region r's population that is evacuated; and

d_ttrad(c,dom,r,d) is the horizontal shift in region d's demand for commodity (c,dom) from region r.

For example, if 74 per cent of regions r's population is evacuated (EVAC_SH(r) = 0.74) then region d reduces its demand at any given prices for r's variety of (c,dom) by 74 per cent. We assumed that d's preference movements are cost neutral: preference shifts by d against damaged regions are offset by favourable movements towards the products of other regions.

Exports

We assume that the rest of Europe (RoEU) loses confidence in all products except electricity from all regions of Poland, particularly from damaged areas. We introduce this assumption through the equation

$$d_ttrad(c,dom,r,RoEU) = -EVAC_SH(r) + [1 - EVAC_SH(r)] * [EVACPOP2 - 1] \quad (3.7)$$

for $r \in \text{Polish regions}$ and $c \in \text{COMLELEC}$

In this equation, d_ttrad(c,dom,r,RoEU) is the horizontal shift in RoEU's demand for commodity (c,dom) from Polish region r. The first term on the RHS of (3.7) is the same as that on the RHS of (3.6). It imparts a demand reduction by RoEU against products (apart from electricity) from damaged regions in Poland. The second term on the RHS imparts a shift in RoEU's demand for products from all regions of Poland. In this term EVACPOP2 is a function of the share of Poland's population that is evacuated from their region (EVACPOP). The function is specified so that its value is 1 if there are no evacuations and close to 0.1 if the evacuation share is close to 1. The function we used is illustrated in Figure 3.2. It has the form:

$$EVACPOP2 = 0.1 + \frac{1}{25 * EVACPOP + 1 / 0.9} \quad (3.8)$$

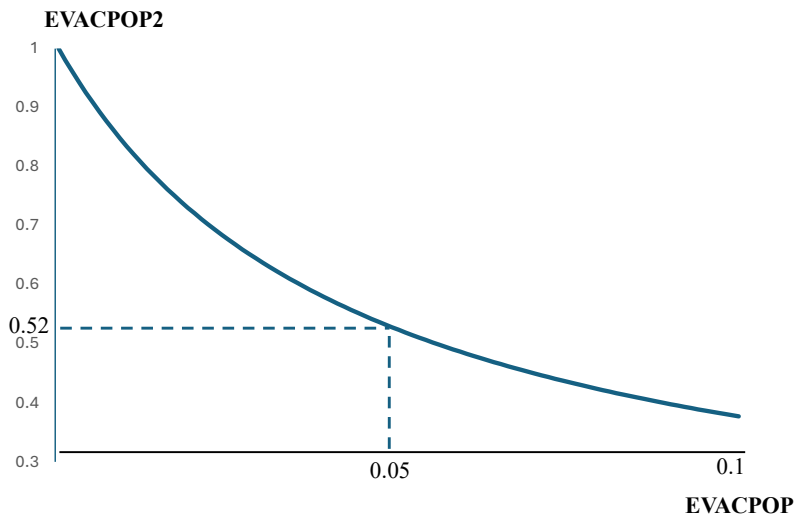
Thus, if the evacuation share for the whole of Poland's population is small (a relatively minor destructive event), then the demand shift by RoEU against products from undamaged Polish regions is negligible. On the other hand, if EVACPOP is substantial, then even for undamaged regions, the demand shift by RoEU is large. For example, if EVACPOP is 0.05, then EVACPOP2 is 0.52 and the demand shift by RoEU against undamaged regions in Poland is -0.48. By including the multiplying factor [1-EVAC_SH(r)] in the second term on the RHS of (3.7), we ensure that the demand shift against region r's products is not more than 100 per cent.

For demands for products from Polish regions by countries outside Europe, we adopted a similar approach to that in equations (3.7) and (3.8).

Other assumptions

We assume zero change in nominal wage rates in all regions of Poland. With prices rises, real wages fall. For RoEU, we assume zero effects for real private and public consumption and real wage rates.

Figure 3.2. Function (3.8) relating EVACPOP2 to EVACPOP



Consistent with a short-run focus, we adopted low values for substitution elasticities in Poland between commodities from different regions of Poland, and between imported commodities and those produced in Poland.

3.2. Destructive events in PL633: sample results from Euro-TERM-PL

Table 3.1 shows Euro-TERM-PL results for four separate destructive events occurring in PL633a337, PL633a380, PL633a514 and PL633a544. These are the four SRAs for which we displayed data in Table 2.5. As indicated in Table 3.1, we assume total destruction zones of radius 1 km and evacuation zones of radius 3 km. The shocks in the simulations can be deduced from Table 2.5. For example, in the PL633a337 simulation, we assume 8,639 deaths, 110,842 evacuations and destruction or idling of 6.89 per cent of PL633's Manufacturing capital, 95 per cent of PL633's Coal-fired electricity generation, etc. Aggregated over industries, the percentages of PL633's and Poland's capital that is no longer available for use are shown in Table 3.1 in the rows labelled "Aggregate capital available". The variables highlighted in Table 3.1 are largely exogenous to the CGE model.

The results confirm that location matters. The four events have the same destructive power in terms of the size of death and evacuation zones. They all occur within a few kilometres of each other. But the economic effects are sharply different. In PL633, the reduction in GDP is 9.5 times greater for the event in a337 than for the event a544 (-16.37 per cent compared with -1.72 per cent). Similarly, for Poland as a whole, the event in a337 reduces GDP by about 10 times more than the event in a544 (-1.49 per cent compared with -0.15 per cent).

The dominant determinant of the GDP results at both the PL633 and Poland levels is the quantity of capital located in the three-kilometre zones and therefore no longer available for use in production. However, that is not the only determinant. Notice, for example, that

Table 3.1. Sample results from Euro-TERM-PL

Site of destructive event	PL633a337	PL633a380	PL633a514	PL633a544
Deaths (1 km zone)	8639	7414	16818	64
Deaths, % of PL633's population	1.16	0.99	2.25	0.01
Evacuations (3 km zone less 1 km zone)	110842	81215	79622	10464
Evacuations, % of PL633's population	14.83	10.87	10.65	1.40
Macro effects in PL633, %				
Population	-15.99	-11.86	-12.91	-1.41
Real household consumption	-15.99	-11.86	-12.91	-1.41
Real government consumption	-15.99	-11.86	-12.91	-1.41
Real GDP	-16.37	-12.13	-12.50	-1.72
Aggregate employment	-17.14	-11.85	-13.98	-1.20
Aggregate capital in use	-15.99	-12.51	-11.30	-2.26
Aggregate capital available	-14.84	-12.02	-8.98	-2.79
Macro effects in Poland, %				
Population	-0.02	-0.02	-0.04	-0.00
Real household consumption	-0.96	-0.71	-0.77	-0.08
Real government consumption	0.00	0.00	0.00	0.00
Real GDP	-1.49	-1.11	-1.12	-0.15
Aggregate employment	-2.14	-1.57	-1.64	-0.20
Aggregate capital in use	-1.11	-0.86	-0.80	-0.14
Aggregate capital available	-0.51	-0.42	-0.30	-0.10

PL633's loss of available capital is greater when the destructive event is centred on a380 than when it is centred on a514 (-12.02 per cent compared with -8.98 per cent), yet the GDP reduction in PL633 is smaller (-12.13 per cent compared with -12.50 per cent).

A good framework for deepening our understanding of the GDP results at both the PL633 and Poland levels is an aggregate production function:

$$\text{gdp} = a + S_k * k + S_\ell * \ell \quad (3.9)$$

where

gdp is the percentage change in real GDP;

k is the percentage change in the input of capital to production, that is capital in use;

ℓ is the percentage change in the input of labour to production (employment);

a is the percentage change in factor productivity brought about by changes in technology; and

S_k and S_ℓ are the shares of capital and labour in GDP with $S_k + S_\ell = 1$.

The aggregate production function tells us that for understanding movements in GDP we should look at productivity, capital in use and employment, not just the reduction in available capital.

We can immediately dismiss the productivity variable, a, from consideration. In the simulations we effectively assumed that there are no changes in production technology.

Next, we consider the percentage change in capital in use, k. This is not the same as the percentage change in capital availability. As explained in subsection 3.1, our simulations introduce variations in the intensity with which available capital is used. In the first three simulations in Table 3.1, the percentage reduction in capital in use in PL633 exceeds the percentage reduction in capital availability, indicating a reduction in the intensity with which capital is used. The opposite is true in the a544 simulation.

What causes variations between simulations in the intensity of capital use in PL633? The main factor is population loss relative to capital availability.

Population is important for demand. In each of the four simulations, real government and household consumption in PL633 decline by the same percentage as population. For government this reflects the assumption built into equation (3.1), and for households it reflects our assumption that incumbent households maintain their baseline level of consumption.

In the a337 and a514 simulations, the percentage loss in population from PL633 exceeds the percentage reduction in capital availability. In the a380 simulation, PL633's percentage loss in capital availability exceeds its percentage loss in population, but the difference is small. In these three simulations, the remaining capital (after the loss of capital in the 3 km zone) used at normal levels of intensity would be more than sufficient to satisfy the reduced demands for products from PL633. Demands for these products are reduced not only by population loss in PL633 but also by adverse preference shifts (discussed in section 3.1). Consequently, in these three simulations there are declines in the intensity with which capital is used. In the a544 simulation, the percentage loss in population from PL633 is significantly less than the percentage reduction in capital availability. Correspondingly, there is an increase in the intensity with which capital is used (capital availability declines by 2.79 per cent but capital in use declines by only 2.26 per cent).

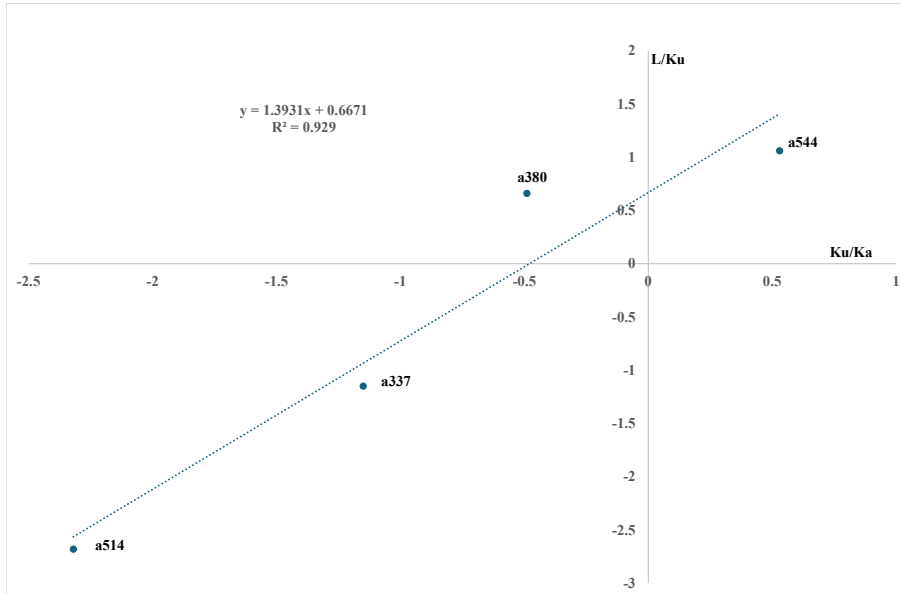
Taking account of the distinction between capital availability and capital in use goes a long way to resolving the puzzle concerning the GDP results for PL633 in the a380 and a514 simulations. In the a380 simulation, there is only a small reduction in the intensity with which PL633's available capital is used (a 12.02 per cent reduction in available capital and a 12.51 per cent reduction in capital in use) reflecting the small gap between the percentage reductions in population and capital availability (11.86 compared with 12.02). In the a514 simulation, there is a sharp reduction in intensity of capital use in PL633 (an 11.30 per cent reduction in capital use compared with 8.98 per cent for capital availability) reflecting the large gap between the percentage reductions in population and capital availability (12.91 compared with 8.98). Nevertheless, the puzzle remains. PL633's capital in use in the a380 simulation declines by more than in the a514 simulation (12.51 per cent compared with 11.30 per cent), yet GDP declines by less (12.13 per cent compared with 12.50 per cent).

The final variable in (3.9) is the percentage change in employment, ℓ . In the a380 simulation, the percentage reduction in employment in PL633 is less than in the a514 simulation (11.85 per cent compared with 13.98 per cent). This resolves the puzzle concerning the GDP results for PL633 in the two simulations: extra employment in the a380 simulation relative to that in the a514 simulation offsets the extra loss of capital in use in the a380 simulation relative to that in the a514 simulation.

But this raises the question of what determines the employment results for PL633 in the four simulations. With the capital results already explained, we can answer this question in terms of movements in ratios of employment to capital in use (L/Ku ratios). In a situation in which there are sharp reductions in the intensity with which capital is used, our model tends to show a reduction in the L/Ku ratio: with plenty of capital there will be a tendency to use capital to replace labour. More formally, movements in L/Ku ratios depend mainly on movements in the ratio of wage rates to rental rates on capital. Wage/rental ratios rise sharply in simulations, such as a514, in which there is a large surplus supply of capital, inducing reductions in L/Ku ratios. The opposite is true in situations in which capital is scarce. Thus, we see in Table 3.1 a close connection between movements in the intensity with which capital is used and movements in L/Ku ratios. This is illustrated in Figure 3.3.

At the Poland level, the government reallocates its expenditures to provide for evacuees [see equation (3.2)] but does not change its overall level of consumption (see discussion of scalarG in section 3.1). With the evacuees no longer providing for their own consumption, household consumption declines. At the same time, there is a shift in preferences by Poland's trade partners against products from Poland. In combination, the declines in consumption and exports leave Poland's capital under-used despite the reduction in capital availability occurring in PL633. Thus, the four simulations in Table 3.1 show reductions for Poland in the ratio of capital in use to capital availability. As already explained in the context of the PL633 results, a reduction in the intensity with which capital is used produces a reduction in the L/Ku ratio. In the four simulations, reductions for Poland in capital in use and the L/Ku ratios explain the reductions in GDP. In accordance with (3.9) the percentage GDP results for Poland lie between those for capital in use and employment.

Figure 3.3. Percentage changes in labour/capital ratios (L/K_u) for PL633 plotted against percentage changes in ratios of capital in use to capital availability (K_u/K_a): results from four simulations



4. Approximating the reduced form of the CGE model by a neural network

For any given values of the exogenous variables, we can obtain values for endogenous variables by solving the model (as in Table 3.1). But that option is not available to the intended users of our DET. To meet the requirement for answers at “*short notice, in a secure environment*”, what these users need is reduced-form equations, that is equations with an endogenous variable on the LHS and a function of exogenous variables on the RHS. Then, by inserting values for exogenous variables on the RHSs, users can easily compute values for endogenous variables.

For the Poland model described in section 3, reduced-form equations for two key sets of variables, GDP and industry employment, can be visualized as:

$$\begin{aligned} \text{gdp}(q) &= G_q(k(r, j); D(r); E(r) \text{ for all } r \in \text{REG}, j \in \text{IND}) \\ q &\in \{\text{nation, 29 regions in Poland}\} \end{aligned} \quad (4.1)$$

$$\begin{aligned} \text{employ}(q, i) &= H_{q,i}(k(r, j); D(r); E(r) \text{ for all } r \in \text{REG}, j \in \text{IND}) \\ \text{for } q &\in \{\text{nation, 29 regions in Poland}\}, \text{ and } i \in \{23 \text{ industries}\} \end{aligned} \quad (4.2)$$

where the exogenous variables are

- $k(r, j)$, the percentage of the capital stock in industry j in sub-national region r that is made unavailable by the destructive event (e.g. capital in the 3 km zone);
- $D(r)$, the number of deaths in region r (e.g. people in the 1 km zone); and

$E(r)$, the number of evacuations from region r (e.g. surviving people in the 3 km zone); and the endogenous variables are
 $gdp(q)$, the percentage change in GDP in region q (national and sub-national) caused by the destructive event; and
 $employ(q,i)$, the percentage change in employment in industry i in region q (national and sub-national).

The challenge for us in creating the DET was to provide code that gives an accurate approximation of the G_q and $H_{q,i}$ functions.

Chen *et al.* (2017) and Rose *et al.* (2017) used regression equations to develop approximations for reduced forms of CGE models that mimic CGE solutions. The regression equations were fitted with a database showing values for exogenous variables and implied values for endogenous variables generated by conducting a few hundred CGE simulation⁵. Dixon *et al.* (2019) developed a mimic tool based on matrices of elasticities of endogenous variables with respect to exogenous variables, also derived from a few hundred CGE simulations. The attractive feature of these tools is that they can be applied easily in-house with negligible turn-around time by users without CGE experience. On the other hand, the number of exogenous variables included in these mimic tools and the range of applicable shocks is limited, and the non-linearities present in the CGE model are generally missed.

For our DET we adopted a new approach based on Neural Network (NN) theory. The new approach overcomes the limitations of the earlier regression/elasticity methods.

4.1. Overview of the NN method

NN methods are not well known in CGE modelling.⁶ Consequently, we provide an appendix that sets out the formal mathematics of the NN estimating method that we used to derive approximations for G_q and $H_{q,i}$. We have also written a paper that includes not only the formal mathematics but also elementary examples of NN calculations, see Dixon *et al.* (2024).

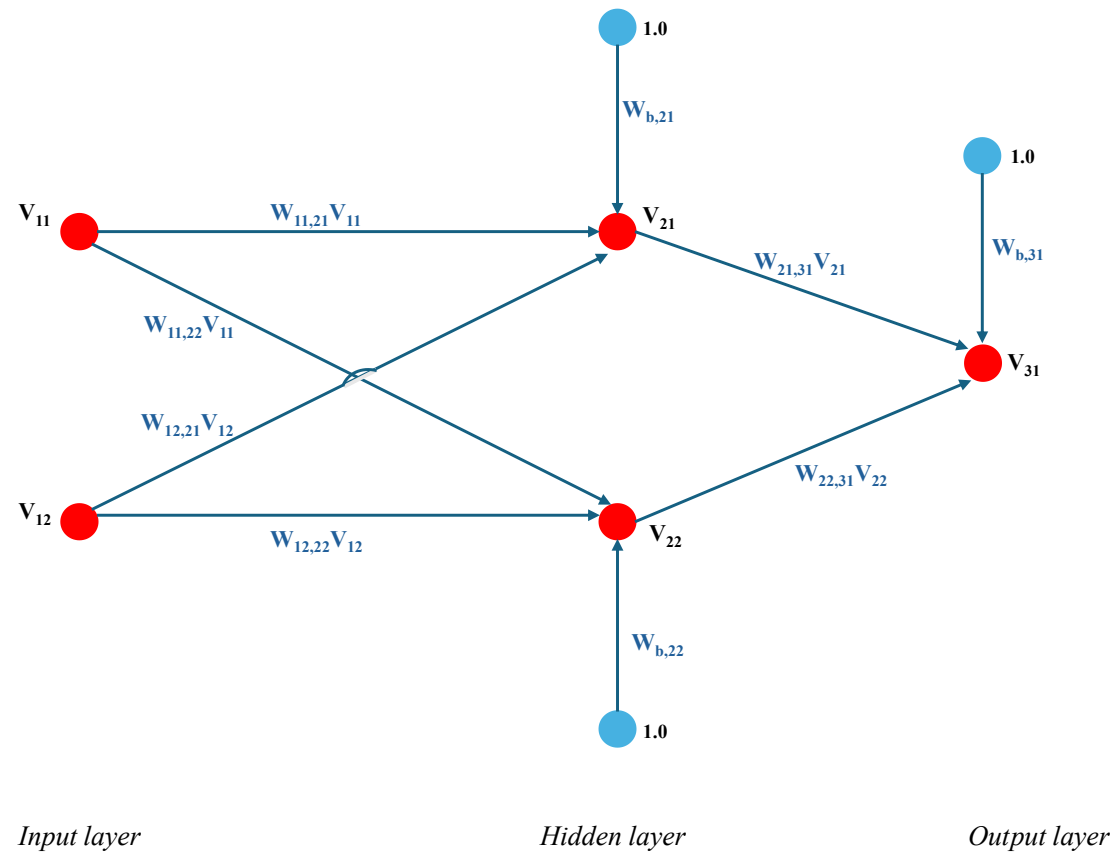
An intuitive visualization of the NN approach is given in Figure 4.1 for a situation in which there are two exogenous variables and one endogenous variable.⁷ Values (V_{11} and V_{12}) for the two exogenous variables are introduced to the Neural Network at two nodes (coloured red) in the input layer. Nodes in the second layer (known as a hidden layer) each receive an input formed as a linear combination of V_{11} and V_{12} plus a constant ($W_{b,21}$, $W_{b,22}$). These inputs are fed into simple non-linear functions which generate values denoted by V_{21} and V_{22} . The node at the third layer (known as the output layer) produces an estimate (V_{31}) of the value of the endogenous variable as a linear combination of V_{21} and V_{22} plus a constant ($W_{b,31}$).

⁵ Regression approximations to reduced forms are also used for sensitivity analysis [e.g. Jin *et al.* (2018)] and for testing explanations of CGE results [e.g. Dixon *et al.* (1982) and Dixon and Rimmer (2013)].

⁶ Applications of neural networks in economics have been largely in financial studies and macroeconomic forecasting, see for example Gogas and Papadimitriou (2021). The only CGE application of which we are aware is Britz *et al.* (2021) who used NN for sensitivity analysis.

⁷ Figure 4.1 is highly simplified. There can be many exogenous and endogenous variables, multiple hidden layers, and different numbers of nodes in each hidden layer. The general specification can be seen in the appendix.

Figure 4.1. An NN approximation of the value of the endogenous variable in a 3-layer computation with 2 exogenous variables and 1 endogenous variable



With given forms for the functions at the hidden layer and given values for the W s (often referred to as *weights* although they can positive or negative and need not sum to one), we could work through the layers to obtain V_{31} for any values of the two exogenous variables. But how do we choose the functional forms for the hidden layer and how do we set the values for the W s?

Surprisingly, it turns out that the answer to the first question is not critical. A wide range of simple functional forms will do. A common choice, and the form we used, is the Rectified linear unit function (ReLU):

$$\text{ReLU}(x) = \max(0, x) \quad (4.3)$$

In choosing the W s, we use a database showing values for exogenous variables and implied values for endogenous variables generated by CGE simulations. However, rather than a few hundred simulations, as we will see shortly, we conducted many thousands of simulations. Having specified the functional forms in the hidden layers and compiled a large database of values for exogenous variables and implied values for endogenous variables, we chose the W s to minimize the sum of the squared differences between the simulated values for the endogenous variables and the values estimated by the NN.

Without a hidden layer the NN approach collapses to ordinary least squares. It is the simple non-linear functions introduced in the hidden layers that give the NN method the power to mimic highly non-linear relationships.

However, fitting an NN with sufficient nodes in hidden layers to approximate accurately reduced forms for a large-scale, multi-regional CGE model requires an enormous number of data points (values for exogenous variables and implied values for endogenous variables). The computational challenge of conducting the required huge numbers of simulations has been eased in recent years by improvements to GEMPACK software for solving CGE models (see Horridge *et al.*, 2018, GEMPACK Manual v. 12.1). At the same time, the availability of easy-to-use libraries for NN have made implementing neural networks routine. Details on our computations are in Dixon *et al.* (2024).

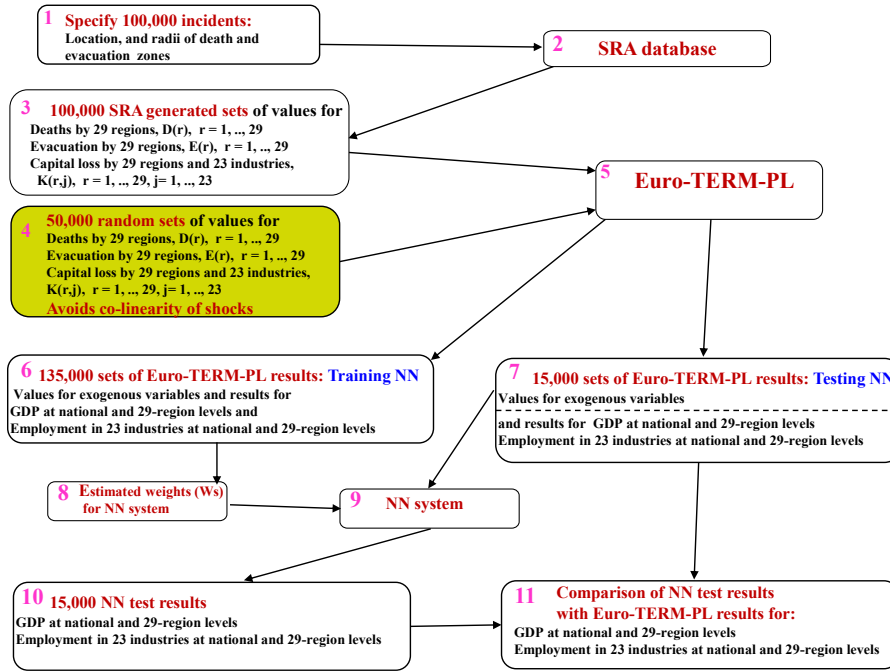
4.2. Applying the NN method in Euro-TERM-PL

Figure 4.2 shows the steps that we undertook in obtaining an NN approximation to the reduced form for Euro-TERM-PL.

The first step (Box 1) was to specify 100,000 destructive events. Locations were chosen by randomized draws from the 600,000 SRAs, and destructive powers were chosen by randomized values for the radii of the total destruction and evacuation zones.

The specifications for the destructive events were fed into the SRA database (Box 2). Then for each event we calculated values for deaths, evacuations and percentage reductions in capital availability by industry and NUTS3 region (Box 3). These values were fed into Euro-TERM-PL as 100,000 sets of exogenous shocks (Box 5).

Figure 4.2. Training and testing an NN system to mimic Euro-TERM-PL results



We also fed another 50,000 sets of shocks (Box 4) into Euro-TERM-PL. These shocks were randomly chosen and not processed through the SRA database. Consequently, they are not necessarily consistent with a realistic destructive event. Their role is to overcome co-linearity problems. In the sets of exogenous variables emerging from Box 3, there is limited variation between some pairs of variables. To allow the NN fitting procedure to distinguish the effect on endogenous variables of variations in one member of such a pair from variations in the other member, it was necessary to introduce sets of exogenous variables in which the links imposed by destructive events are broken.

With the inputs from Boxes 3 and 4, Box 5 generates 150,000 data points. Each data point consists of values for the vector of exogenous variables and the implied values for the vector of endogenous variables. We randomly split these 150,000 data points into two groups: 135,000 for training (Box 6) and 15,000 for testing (Box 7).

Training refers to the process of finding the optimal values for the W_s . We did this in Box 8 by choosing W_s to minimize the sum of the squared differences between the 135,000 vectors of simulated values for the endogenous variables and the values estimated through the layers of NN equations. We inserted the optimal W_s into the equations of the NN system to complete the approximation of the reduced-form for Euro-TERM-PL (Box 9).

Testing refers to the process of seeing how accurately the NN approximation to the reduced form reproduces the the simulated values for the endogenous variables. For testing, we used

the 15,000 data points from Box 7. These were not used in training. We carried out the test by feeding the 15,000 vectors of exogenous variable from Box 7 into the NN system in Box 9. This gave us 15,000 approximate solutions for the vectors of endogenous variables (Box 10). In Box 11 we compared these NN approximations with the 15,000 simulated values for the vectors of endogenous variables from Box 7.

The 15,000 dots in each of Figures 4.3 and 4.4 display the comparison for national GDP and employment in a major exporting region (PL42, a region in the north west of Poland). A perfect fit generates a dot on the 45-degree line. The tight fit shown in the figures applies to the wide range of the macro and regional variables that we tested.

In conducting the 135,000 training simulations and the 15,000 test simulations, we allowed variations in the exogenous variables over the full ranges of what we considered plausible for the destructive events under consideration. As can be seen from Figure 4.3, the test simulations produced national GDP results in the range zero to -22 per cent. For employment in the selected region, the range of Euro-TERM-PL results shown in Figure 4.4 was even greater, from slightly positive to -40 per cent. Reassuringly, the NN approximations in both figures are accurate over the entire range of Euro-TERM-PL results.

5. Concluding remarks

Planning responses for possible destructive events requires realistic information on their likely economic effects. These effects depend on the location of the event and its destructive power. This paper describes a destructive events tool (DET) for Poland. Users of this tool can project the economic effects of destructive events occurring at any location in Poland specified by latitude and longitude. The power of the event is characterized by user-specified total destruction and evacuation zones.

The DET quantifies the immediate reductions in the ability of affected regions to supply products and labour. It shows indirect effects on other regions emanating from upstream and downstream linkages. The effects on regional economies of influxes of evacuees and associated government expenditures are also included. Information from the DET could be a valuable input in implementing the response to a major destructive event in the first three months. However, that is not the only possible application. DETs can be used to give rankings of locations by the economic damage caused by a “standardized” event. Colon *et al.* (2021) shows how this can be done. Using their model of Tanzanian roads, they calculate economic damage for one-week, flood-related road closures occurring at different points in the road network. In this way, they provide information to guide the allocation of flood-mitigation funds to locations with the highest expected payoffs. Similar applications could be made with our DET. For example, a series of simulations could be conducted to rank locations by economic damage from a standardized terrorism attack, e.g. a dirty bomb of a given magnitude. The aim would be to provide input to allocation decisions concerning funds for security operations.

The building blocks for the Polish DET are: an SRA database; a multi-regional CGE model; and a reduced-form approximation. In the rest of this conclusion, we discuss how these building blocks could be improved and how the range of application of the DET could be extended. We also discuss the feasibility of creating DETs for many countries. We find that our methodology is generally applicable, although the quality of the input data will vary from country to country and with the resources that can be devoted to refining it.

Figure 4.3. Percentage effects on national GDP generated by Euro-TERM-PL and the NN approximation system in 15,000 out-of-sample tests

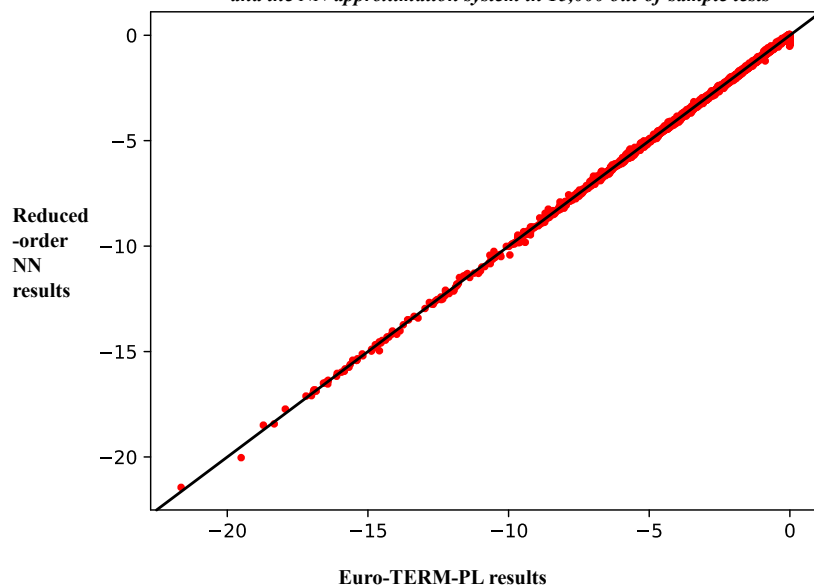
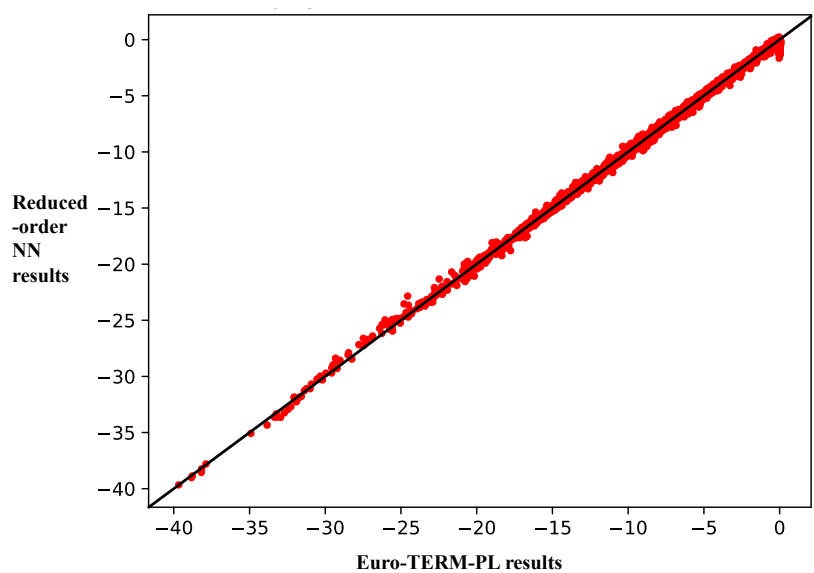


Figure 4.4. Percentage effects on employment in a major exporting region (PL42) generated by Euro-TERM-PL and the NN approximation system in 15,000 out-of-sample tests



SRA data

The main difficulty in creating the SRA database for the Polish DET was allocating data on the industrial composition of activity at the sub-national regional level (NUTS3 data) to the SRA level. This involved formulas informed by Open Street Maps, the Global Power Plant database and NASA population data. The weighting schemes in these formulas are based on judgement. Superior data for small regions that could be used for SRAs are available for some countries, see for example, the Hazus manual for the U.S. [FEMA(2022)] and the sources cited by Yamano *et al.* (2007) for Japan. Most countries have employment by industry data at a subnational regional level, and the other data sources we used for Poland are almost globally available. Thus, the approach we used for Poland could be implemented for most countries.

Multi-regional CGE model

The second requirement for building DETs is an economic model with sufficient regional and industrial definition to enable translation of shocks specified at an SRA level into implications for endogenous variables at the sub-national and national levels. TERM models, of which Euro-TERM-PL is an example, are suitable for this task. Building TERM models requires national input-output data and sub-national regional industry data of the same type as used in SRA estimation. The national data requirements can be met by accessing databases prepared by the GTAP group at Purdue University, see Aguiar *et al.* (2023). GTAP provides national data for 65 industries in about 160 countries.

The TERM model we constructed for Poland was short-run comparative static. This could be extended to long-run comparative static or to fully dynamic, see for example Dixon *et al.* (2017). With long-run extensions the model could include restoration activities. It might also be possible to show how property values would be affected in damaged regions relative to those in regions receiving evacuees.

Even within our short-run focus, major improvements in the modelling might be possible. Within a three-month horizon we could use the CGE model to trace out week-by-week scenarios that might include preliminary restoration activities and implementation of resilience tactics. We could also draw on engineering data to build into the model the network of electricity generation and distribution within a sub-national region. In its present form, the DET requires active user intervention to take account of power interruptions to industries and households in SRAs disjoint from the event location.

In adding complications to the CGE model, a balance must be maintained between inbuilt realism and the need to have a tool that is general enough to be applied by non-CGE modellers to a wide range of events.

A reduced-form approximation

Creating the NN approximation to the reduced form for the CGE model was a major computational task. We anticipate that the computational burden could be reduced in future applications by choosing the training and test simulations via a variant of the hyper-cube method adopted in Rose *et al.* (2017). Even without refinements, our Polish example establishes the feasibility of the NN method. It shows the potential for this method to increase dramatically the detail and accuracy that can be built into mimic equations for CGE reduced forms.

Appendix. Mathematical representation of the NN method for approximating the reduced form of a CGE model

Intuitive examples showing how this method works are in Dixon *et al.* (2024). Here we set out the formal mathematics.

The NN optimization problem for determining the W s takes the form:

choose values for W s to minimize

$$\sum_{k=1}^{NJ} \sum_{t=1}^T \left(V_k^{\text{Endo}}(t) - V_{jk}(t) \right)^2 \quad (\text{A1})$$

subject to

$$V_{1r}(t) = V_r^{\text{Exog}}(t) \quad \text{for all } t \text{ and } r = 1, 2, \dots, N1 \quad (\text{A2})$$

$$V_{2r}(t) = F_{2r} \left(\sum_{\ell=1}^{N1} W_{1\ell,2r} * V_{1\ell}(t) + W_{b,2r} \right) \quad \text{for all } t \text{ and } r = 1, 2, \dots, N2 \quad (\text{A3})$$

... ..

$$V_{(J-1)r}(t) = F_{(J-1)r} \left(\sum_{\ell=1}^{N(J-2)} W_{(J-2)\ell,(J-1)r} * V_{(J-2)\ell}(t) + W_{b,(J-1)r} \right) \quad \text{for all } t \text{ and } r = 1, 2, \dots, N(J-1) \quad (\text{A4})$$

and

$$V_{jk}(t) = \sum_{\ell=1}^{N(J-1)} W_{(J-1)\ell,jk} * V_{(J-1)\ell}(t) + W_{b,jk} \quad \text{for all } t \text{ and } k = 1, 2, \dots, NJ \quad (\text{A5})$$

In (A1) - (A5),

$V_r^{\text{Exog}}(t)$ is the r^{th} component of $V^{\text{Exog}}(t)$ and $V_k^{\text{Endo}}(t)$ is the k^{th} component of $V^{\text{Endo}}(t)$ where $(V^{\text{Exog}}(t), V^{\text{Endo}}(t))$ is the t^{th} data point, that is the vector of exogenous variables and the implied vector of endogenous variables in the t^{th} training simulation. In the Poland example, $T = 135,000$.

J is the number of layers in the NN. In Figure 4.1, there is only one hidden layer giving $J = 3$. In our Poland example, we used 4 hidden layers, giving $J = 6$.

$N1$ is the number of nodes in the first layer which must be the same as the number of exogenous variables.

Nj , $j = 2, \dots, J-1$ is the number of nodes in the j^{th} layer (the $j-1^{\text{th}}$ hidden layer). This is a user choice. In Figure 4.1, $N2 = 2$. In our computations in the Poland example, $N2$, $N3$, $N4$ and $N5$ are each about 800.

NJ is the number of nodes in the output layer (the last layer) which must be the same as the number of endogenous variables. In Figure 4.1, $NJ = 1$. In our computations in the Poland example, NJ is several hundred.

$V_{1r}(t)$, $r = 1, \dots, N1$, is the value at the r^{th} node in the first layer in the t^{th} training simulation. This is $V_r^{\text{Exog}}(t)$.

$V_{jr}(t)$, $j = 2, \dots, J-1$ and $r = 1, \dots, N_j$, is the value at the r^{th} node in the j^{th} layer in the t^{th} training simulation.

$V_{jk}(t)$, $k = 1, \dots, N_J$, is the value of the k^{th} endogenous variable in the output layer (the last layer) of the NN. This is the NN approximation to the value of the k^{th} endogenous variable in the t^{th} training simulation.

$F_{2r}, \dots, F_{(J-1)r}$ are the functions used in the hidden layers. The value at the r^{th} node in the j^{th} layer is determined by applying F_{jr} to a linear combination of the node values in the previous layer $\left(\sum_{\ell=1}^{N_{(j-1)\ell}} W_{(j-1)\ell,jr} * V_{(j-1)\ell}(t) + W_{b,jr} \right)$. Values in the output layer are simply linear combinations of the node values in the previous layer. In the Poland example, the F functions are ReLU.

With given values for the W s, we could work through (A2) to (A5) to obtain values for $V_{jk}(t)$, $k = 1, \dots, N_J$. The objective is to set the W s so that the resulting fitted values for $V_{jk}(t)$, $k = 1, \dots, N_J$ minimize (A1). With the optimal W s, the fitted values for $V_{jk}(t)$, $k = 1, \dots, N_J$, are the NN approximations to the endogenous variables from the CGE model.

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