Constructing a Destructive Events Tool Using Small Rectangular Areas, Computable General Equilibrium Modelling and Neural Networks

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Abstract

This paper describes a destructive events tool (DET) for anticipating the national and regional economic effects of a destructive event occurring at any latitude/longitude in a country. The event is characterized by areas of complete destruction and evacuation. The event could be a natural disaster, major industrial accident, or terrorist attack.

The key ingredient for a DET is data showing population and employment by industry in small rectangular areas (SRAs). In the Poland DET, motivating the paper, there are 600,000 SRAs, each 0.5 sq km. This spatial resolution greatly improves the accuracy of the estimation of the economic impacts of events where physical impacts vary substantially across small areas.

The second ingredient is an economic model with sufficient regional/industrial definition to translate shocks at an SRA level into implications at the sub-national and national levels. This requirement is met by a multi-regional computable general equilibrium (CGE) model.

The final ingredient is an approximation for the model's reduced form. This is necessary so that the DET can be applied by organizations, without in-house CGE expertise, that need quick turnaround in a secure environment. We implement an approximation method for CGE reduced forms based on Neural Networks.

Key words:

Destructive events tool; Small rectangular areas; Multi-regional computable general equilibrium models; Neural network approximations to reduced forms

Jel codes

C81, C68, C45, H84

Contents

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1. Introduction

This paper describes a destructive events tool (DET) that we created for an organization 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*. The events that could be analyzed with DET include natural disasters and major industrial accidents.

We created DET in three stages.

First, we had to deal with the "any location" requirement. To do this we needed to assemble data for a country 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 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. While organizations without CGE expertise can go to outside providers, this is not compatible with quick turnaround and confidentiality. To overcome these difficulties, we used 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.

The paper is organized along the lines of the three stages. 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 explains the creation of the NN approximation to the reduced-form of the CGE model. The concluding remarks in section 5 discuss the feasibility of building DETs for countries other than Poland.

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), shown in 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), Manufacturing (4.75 per cent) and Finance (4.42per 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.

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 an SRA is slightly less than that of the south boundary, but there is only a few centimetres difference (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, 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.

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
Value added (returns to primary factors, $US million)			
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 & Retai;	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 Communication	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 Dwellng	430	14431	2.89
Total	14528	407338	3.44

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

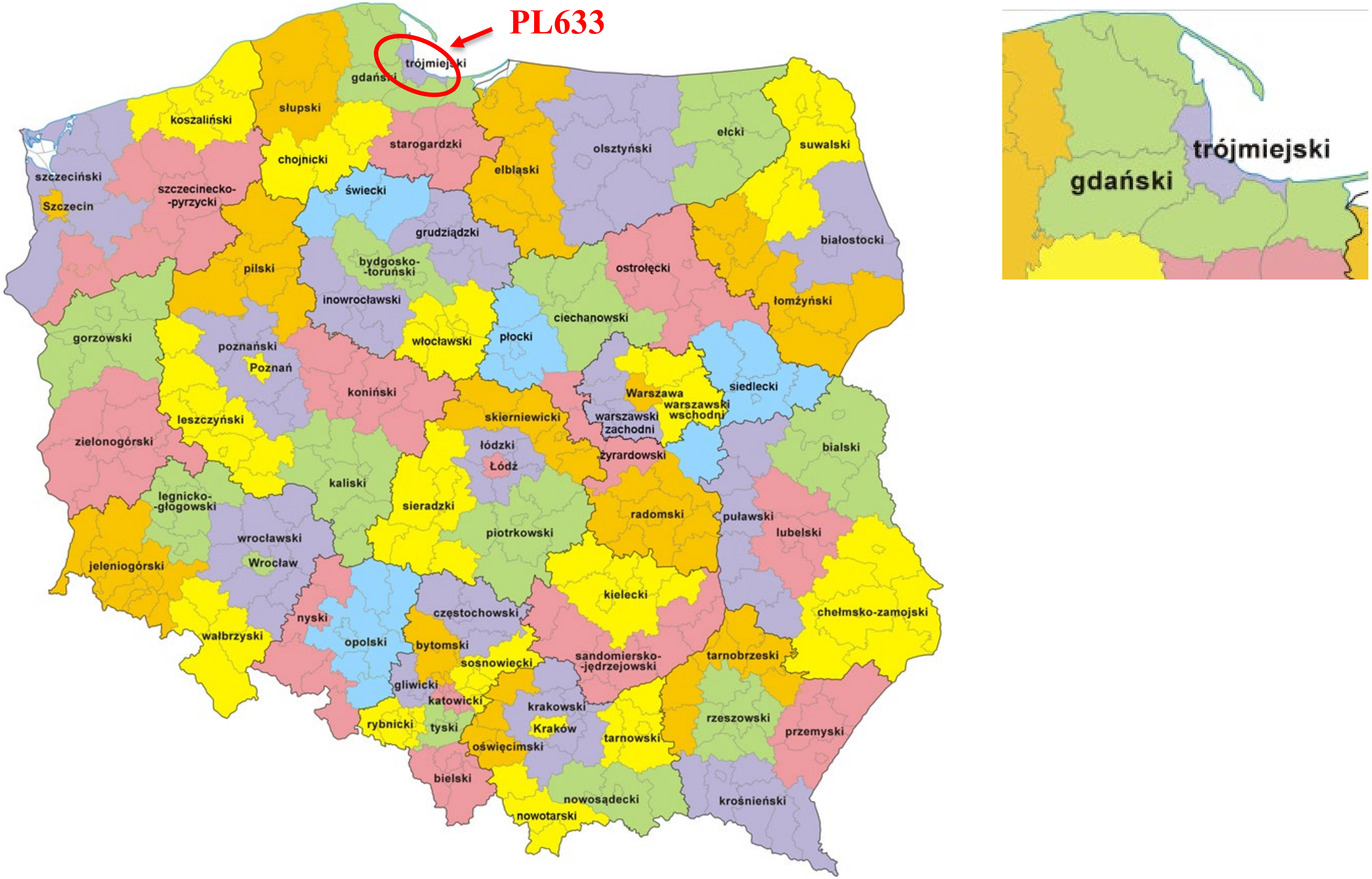
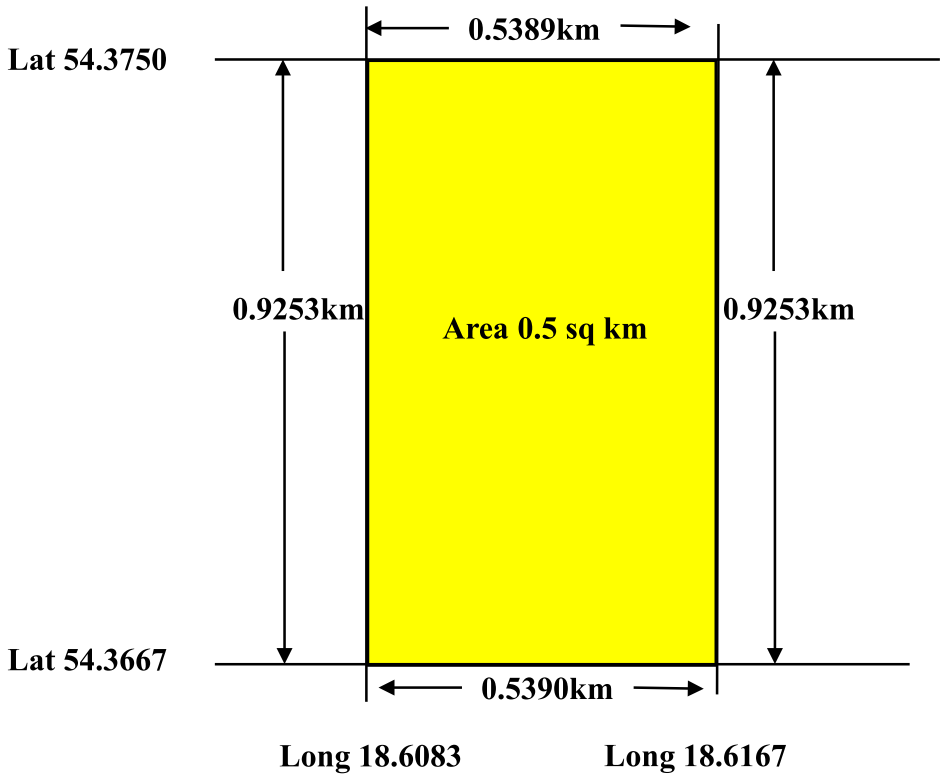


Figure 2.2. PL633 partitioned into 829 small rectangular areas

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



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

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 and a Helipad (confirmed in Figure 2.7). 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.

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	TferryTrmnal	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)

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

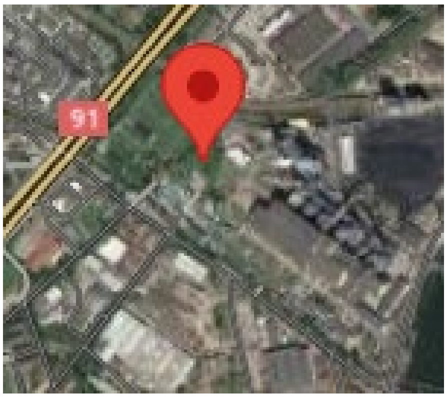
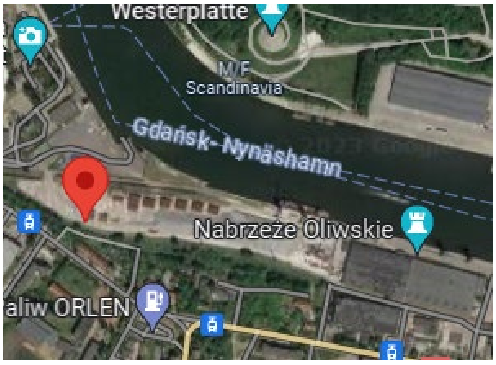


Figure 2.6. Google Maps satellite and street view centred on PL633a514 (predominantly residential)

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)



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 there are 6 power plants in PL633. We assigned each of these to the SRA whose centroid is closest to the coordinates of the power plant (two in PL633a154). Our power plant data are given in Table 2.3. The assignments to SRAs can be checked using google maps.

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).

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

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

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

where

VA(r,j) is value added (returns to labour, capital and land) 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).

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, illustrated in Table 2.2. For these industries we calculated the allocating fractions according to

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

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 characteristics that we included in OSM(21) are University, School, Kindergarten and College. 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 is 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 Dwelling	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 Electricity generation, Recreation and 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 10,465 (= 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 81,215 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.

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 86,865 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).

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

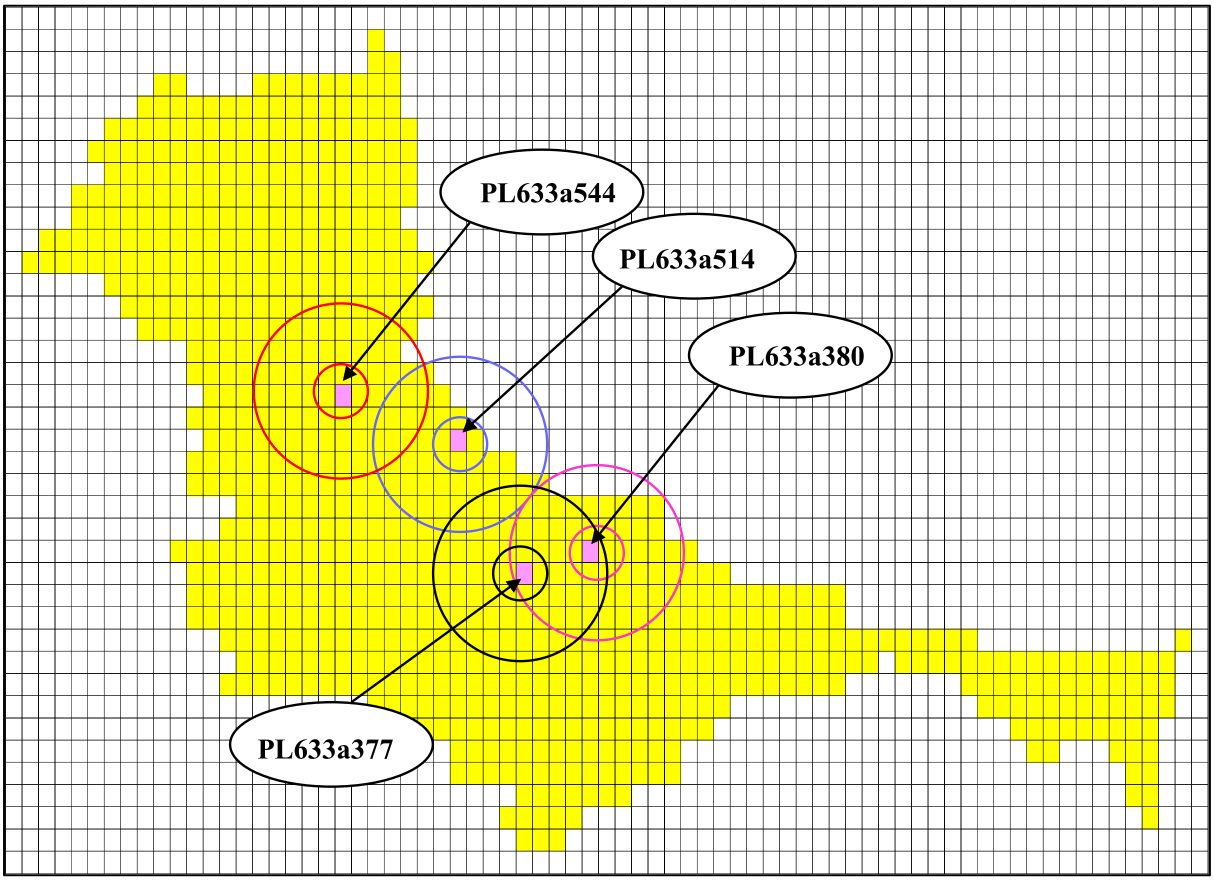


Table 2.5. Information for calculating population and capital effects of destructive events in selected SRAs in PL633

Ground zero	PL633a337		PL633a380		PL633a514		PL633a544	
Radius around ground zero	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 OwnerDwellng	1.16	15.99	0.99	11.86	2.25	12.91	0.01	1.41

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

For DET, we need an economic model that accepts shocks representing capital destruction or idling by 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.

3.1. Euro-TERM-PL

To meet this requirement, we constructed Euro-TERM-PL. As with all TERM[1] models, this is a multi-regional computable general equilibrium (CGE) model. Created for this project, 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 strong flows of capital and labour between the regions of Poland.

The standard specifications in TERM models are documented elsewhere, see for example, Wittwer (2017). Here, we describe assumptions and modifications introduced to facilitate simulations of destructive events.

The client was primarily interested in short-run effects, 3 months. Consequently, the modifications focused on improving the realism of the model's results for the short run. We were not concerned with restoration activities.

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. However, we are exploring other options. If the evacuation zones barely overlap with a region, then it might be realistic to allow that region to receive evacuees.

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:

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

[1] **T**he **E**normous **R**egional **M**odel. The TERM methodology was pioneered by Horridge *et al* (2005). In recent years, it has been developed and extended by Wittwer and other colleagues at the Centre of Policy Studies, see for example Wittwer (2017 and 2024) and Wittwer and Horridge (2018).

$$\Delta GOV(c,r) = F\_G(c) * \left(\sum_{d \in SEvac} \frac{EVAC(d)}{POP(d)} * GOV(c,d) \right) * \left(\frac{GOV(c,r)}{\sum_{rr \in SReceive} GOV(c,rr)} \right)$$

$$+ F\_H(c) * \left(\sum_{d \in SEvac} \frac{EVAC(d)}{POP(d)} * HOU(c,d) \right) * \left(\frac{EVACIN(r)}{\sum_{rr \in SReceive} EVACIN(rr)} \right) \quad (3.2)$$

$$- GOV(c,r) * scalarG$$

for all $c \in Com$ and for all $r \in SReceive$

In (3.1),

SEvac is the set of damaged regions (regions from which evacuations take place);

Com is the set of all commodities;

ΔGOV(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);

ΔGOV(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 = 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 concerned with 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 value 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 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:

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

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 in the post-event situation, 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:

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

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:

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

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 to 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 to 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 domestic[2] 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. We assume that all regions in Poland adjust their preferences against all products except electricity from the damaged regions (those suffering positive evacuations). The preference shifts for region d are set according to:

$$d\_ttrad(c,dom,r,d) = -EVAC\_SH(r) \quad d,\ r \in \text{Polish regions and } c \in \text{COMLELEC} \tag{3.6}$$

where

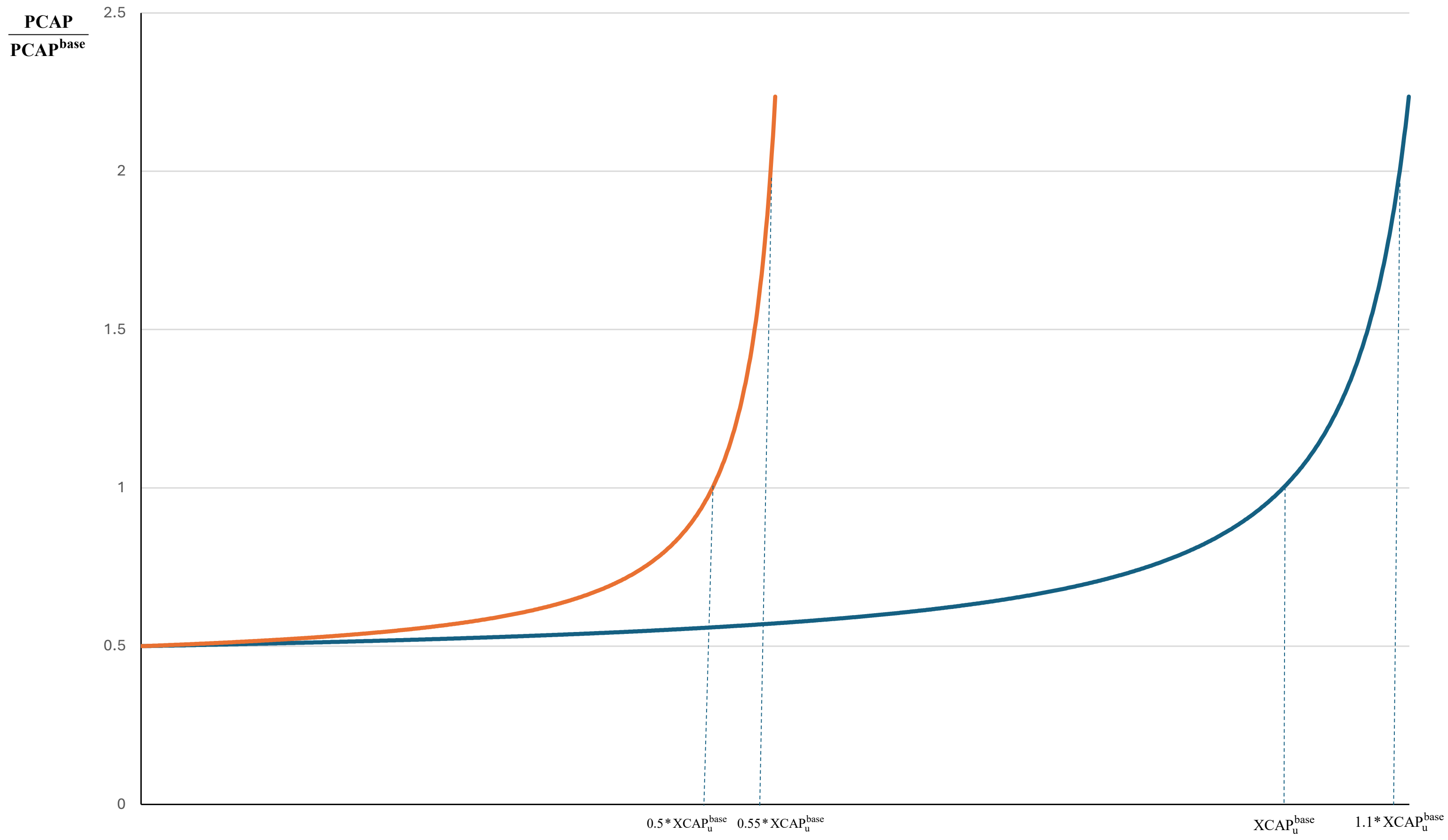
COMLELEC is the set of all commodities excluding electricity;

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.

2 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



In our modelling, the values for the d_ttrad's are translated into percentage movements in the preference variables [atrad(c,dom,r,d) for all r] appearing in d's CES function for (c,dom). We assumed that the atrad movements are cost neutral for region d: a preference shift by d against damaged regions are offset by uniform favourable movements in atrad(c,dom,rr,d) for all rr.

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

$$\text{d\_ttrad(c,dom,r,RoEU)} = -\text{EVAC\_SH(r)} + \left[1 - \text{EVAC\_SH(r)}\right] * \left[\text{EVACPOP2} - 1\right]$$

$$\text{for r} \in \text{Polish regions and c} \in \text{COMLELEC} \qquad (3.7)$$

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:

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

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.

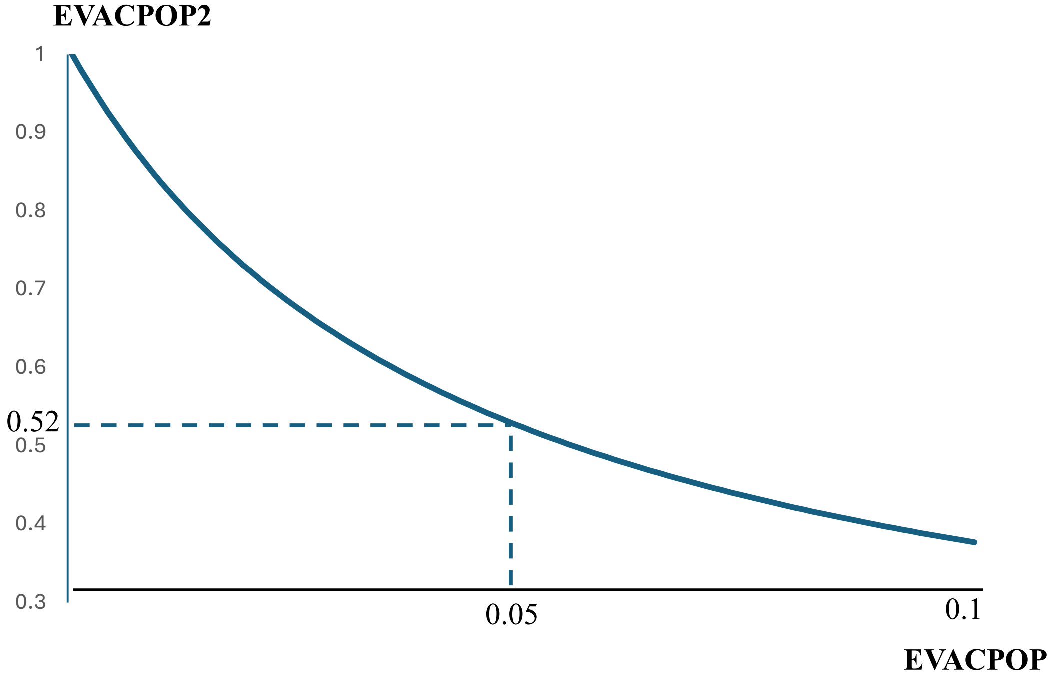
For demands for products from Polish regions by countries outside Europe, we adopted a similar approach to that in equations (3.7) and (3.8).

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.

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.

Figure 3.2. Function (3.8) relating EVACPOP2 to EVACPOP



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 that we applied 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 can be 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 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).

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 pop	1.16	0.99	2.25	0.01
Evacuations (3 km zone less 1 km zone)	110842	81215	79622	10464
Evacuations, % of PL633's pop	14.83	10.87	10.65	1.40
Macro effects in PL633, %				
Population	-15.99	-11.86	-12.91	-1.41
Real household cons	-15.99	-11.86	-12.91	-1.41
Real government cons	-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 cons	-0.96	-0.71	-0.77	-0.08
Real government cons	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

From Table7xxxx.xlsx in c:\dixon\consult\2024\DTRA\Mainpaper   Tab file: Tbigaq4xx.tab Cmf files simxxxx337.cmf etc

Results from c:\dixon\consult\2024\fromFlo130324\Gdansk\sim simxxxx337.sl4, simxxxx380.slr, simxxxx514.sl4, simxxxx544.s

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

$$gdp = a + S_k * k + S_\ell * \ell \qquad (3.9)$$

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 (employment) to production;

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 in the discussion labelled "*Capital supply curve: allowing for excess capacity*", 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).

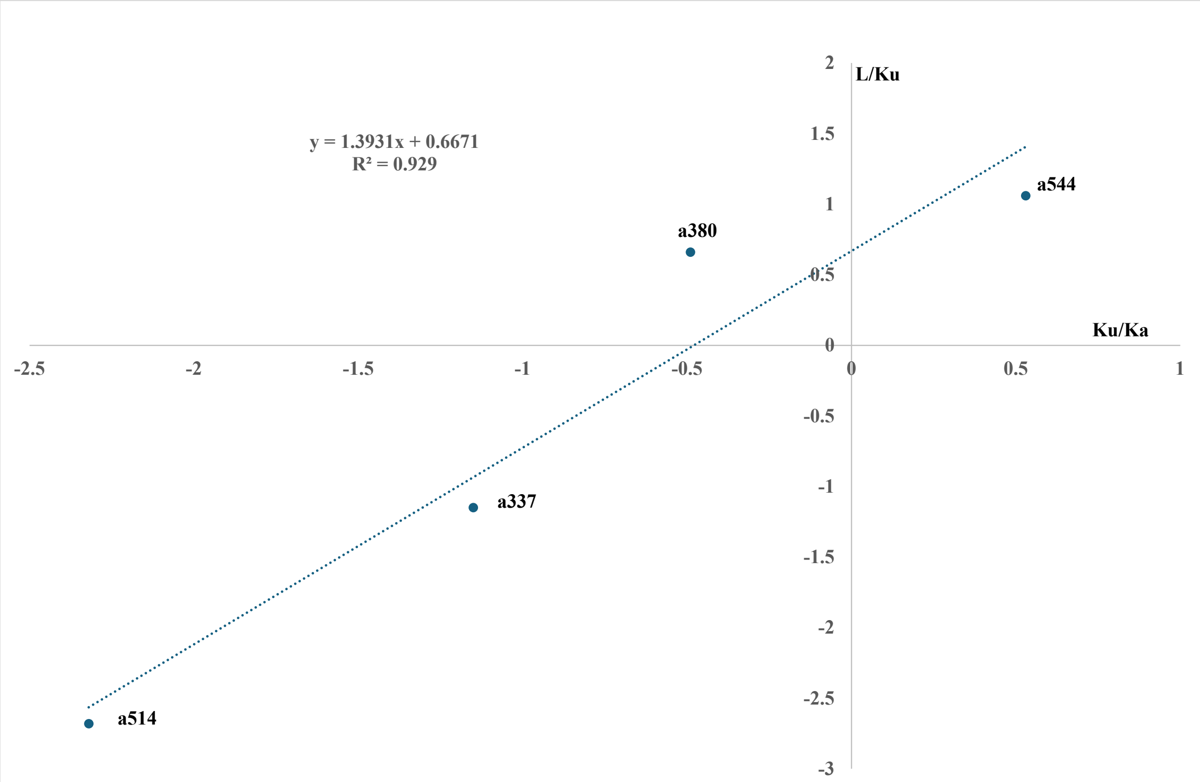
Taking account of the distinction between capital availability and capital in use goes a long way to resolving the puzzle concerning the GDP results for PL633 in the a380 and a514 simulations. In the a380 simulation, there is only a small reduction in the intensity with which PL633's available capital 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 (8.98 per cent compared with 11.30 per cent) 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/Ku) for PL633 plotted against percentage changes in ratios of capital in use to capital availability (Ku/Ka): 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 our client. To meet the requirement for answers at *"short notice, in a secure environment"*, what the client needs 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, the client can easily compute values for endogenous variables.

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

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

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

where the exogenous variables are

k(r,j), the percentage of the capital stock in industry j in 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 was to provide code usable by the client that gives an accurate approximation of the G_q and $H_{q,i}$ functions.

Rose *et al.* (2017) used regression equations to develop approximations for reduced forms of CGE models that clients use to mimic CGE solutions relevant to their interests. 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 simulation[3]. 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 clients 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 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.[4] 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).

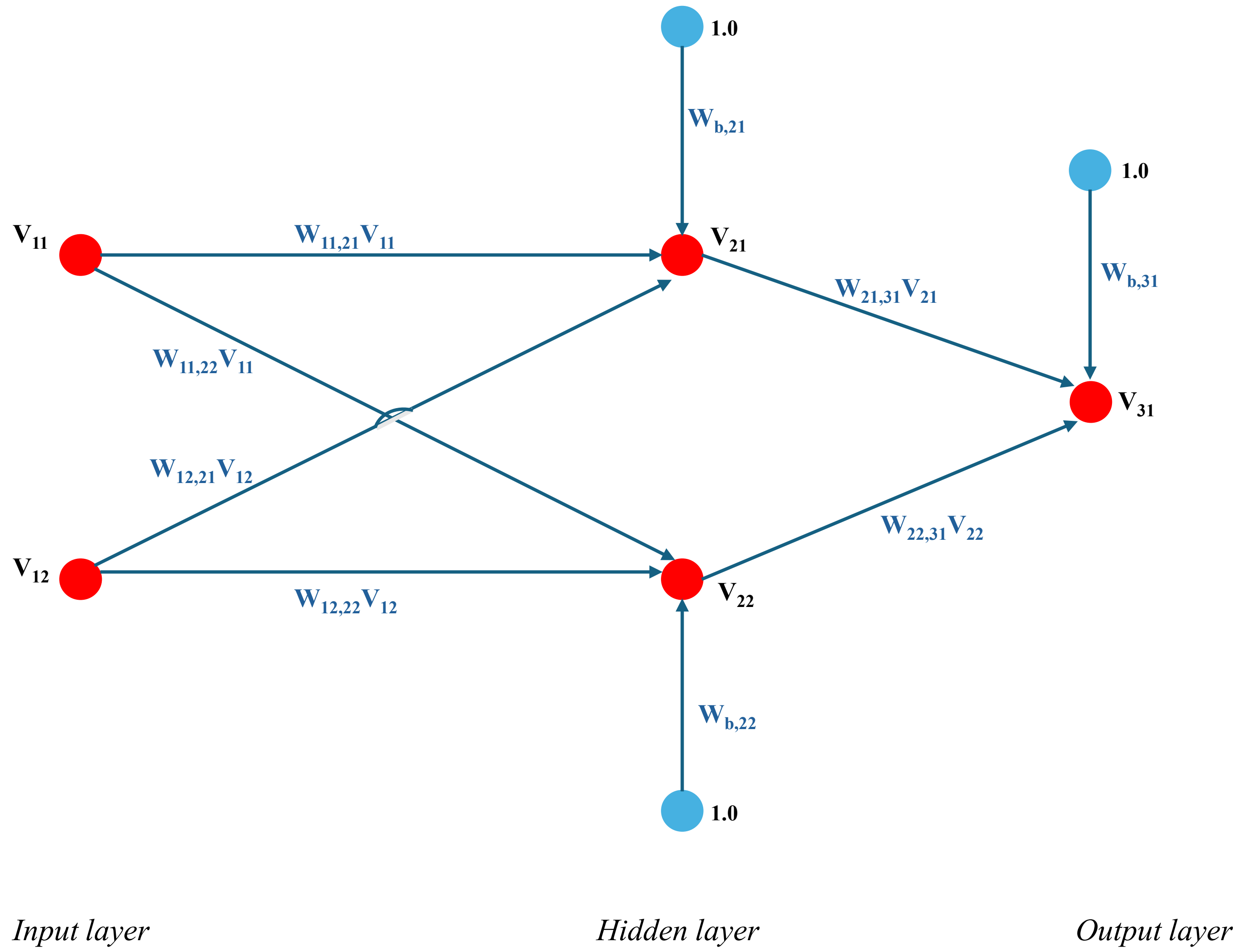
An intuitive visualization of the NN approach is given in Figure 4.1 for a situation in which there are two exogenous variables and one endogenous variable.[5] Values (V_{11} and V_{12}) for the two exogenous variables are introduced to the Neural Network at two nodes (coloured red) in the input layer. 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

[3] Regressions 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)].

[4] 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.

[5] 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



the value of the endogenous variable as a linear combination of V_{21} and V_{22} plus a constant ($W_{b,31}$).

With given forms for the functions at the hidden layer and given values for the Ws (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 Ws?

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):

$$\mathrm{Re\,LU}(x) = \max(0, x) \tag{4.3}$$

In choosing the Ws, we use a database showing values for exogenous variables and implied values for endogenous variables generated by CGE simulation. 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 Ws 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 with a large-scale, multi-regional CGE model has been dramatically eased in recent years by major 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).

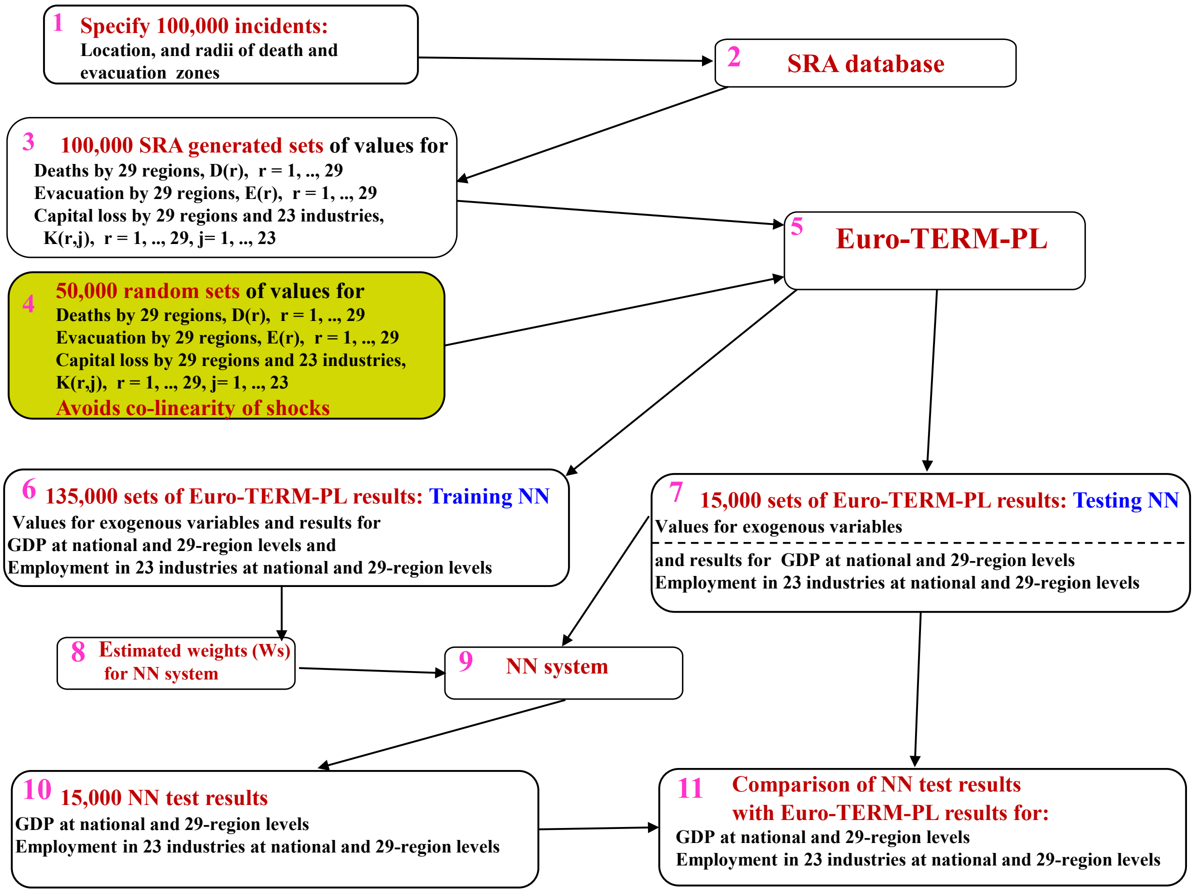
4.2. Applying the NN method in Euro-TERM-PL

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 Ws. We did this in Box 8 by choosing Ws 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 Ws 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 in characterized by user-specified total destruction and evacuation zones.

There are three building blocks for a DET: SRA data; an economic model; and an approximate reduced form. The methods described in this paper for putting in place the building blocks for Poland could be applied for many other countries.

SRA data

The key requirement for building DETs is estimates at the SRA level of population, and of employment disaggregated by industry. Population estimates are available worldwide from NASA. Estimates of industry employment at the SRA level are made by allocating data from a sub-national regional level.

Data on employment for sub-national regions are widely available. For example, EUROSTAT publishes data on employment by industry for western European countries divided into about 1200 sub-national regions (401 for Germany, 73 for Poland, 101 for France, etc). In the U.S., the Bureau of Economic Analysis publishes data on employment for about 3,000 counties. For China, data on employment by industry in about 365 regions is available from provincial and national yearbooks. However, the Chinese data are somewhat out of date and may lack credibility in some aspects. Other countries on which the team at the Centre of Policy Studies has worked with sub-national data on employment by industry in recent years include Australia, Austria, Germany, Finland, Sweden, Norway, Denmark, Italy, Brazil, Philippines, India, Vietnam, Indonesia, Japan, Korea, New Zealand, Sri Lanka, South Africa and Canada.

For some countries, putting together sub-national industry data is difficult, but almost always possible. For example, preliminary investigation of Russian data indicates availability of data on 20 industries in 90 regions. These data are not in ideal form, but they are usable.

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

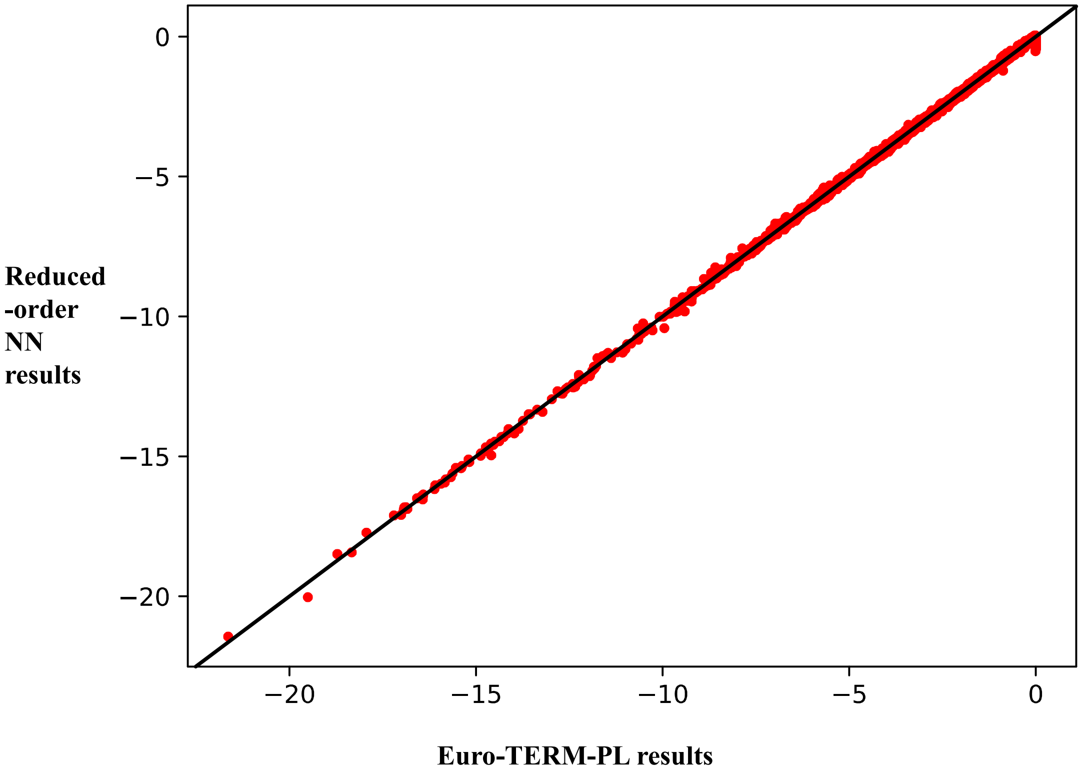
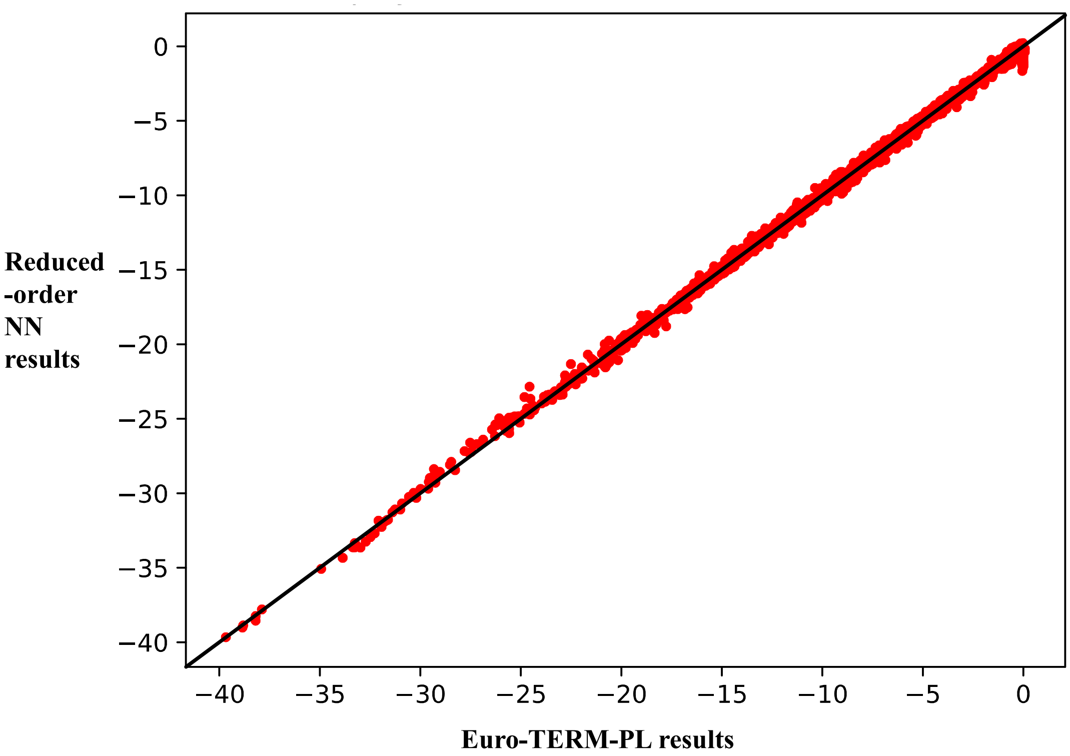


Figure 4.4. Percentage effects on employment in a major exporting region (PL42) generated by Euro-TERM-PL and the NN approximation system in 15,000 out-of-sample tests



For Poland, we allocated sub-national data to the SRAs using Open Street Maps (OSM) and the Global Power Plant database provided by the World Resources Institute.

Open Street Maps is a global crowed-sourced geographic database that provides geospatial data released under a free licence. Many countries are fully mapped by OSM. For these countries, OSM data can provide extremely accurate land-use, transport, utility and other infrastructure data down to individual buildings. In regions where OSM coverage is poor, the available data can nevertheless be used to estimate land-use.

The Global Power Plant Database is an open-source database of power plants around the world. It gives latitude and longitude for approximately 35,000 power plants in 167 countries.

Our assessment is that SRA databases could be constructed for most countries. The quality of the data varies, but key data on the location of population centres, power plants, industrial capacity, airports and other major infrastructure items is generally available.

The economic 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 industry data. The national data requirements can be met by accessing databases prepared by the GTAP group at Purdue University. GTAP provides national data for 65 industries in about 160 countries. The requirement for sub-national data is the same as that discussed above for the SRAs.

An approximate reduced form

The third requirement for building a DET is an accurate approximation to the reduced form of the CGE model. This enables the tool to be used by organizations requiring quick turnaround in a secure environment. By exploiting improvements in CGE software and in libraries for NN, we derived an NN-approximation to Euro-TERM-PL's reduced form.

The feasibility of NN methods dramatically increases the detail and accuracy that can be built into mimic equations for CGE reduced forms. An NN system can include a large number of exogenous variables with wide ranges of shocks and can capture the non-linearities of the CGE model. The NN system described in this paper produces results that closely match those from a large-scale CGE model for wide variations in several hundred exogenous variables. In scope and tested accuracy, this is well beyond any previous mimic system for a CGE model.

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

The NN optimization problem for determining the Ws takes the form:

choose values for Ws to minimize

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

subject to

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

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

… … …

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

and

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

In (A1) - (A5),

$V_r^{Exog}(t)$ is the r[th] component of $V^{Exog}(t)$ and $V_k^{Endo}(t)$ is the k[th] component of $V^{Endo}(t)$ where $\left(V^{Exog}(t), V^{Endo}(t)\right)$ 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, …, J-1 is the number of nodes in the j[th] layer (the j-1[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, …, N1, is the value at the r[th] node in the first layer in the t[th] training simulation. This is $V_r^{Exog}(t)$.

$V_{jr}(t)$, j = 2, … , J-1 and r = 1, …, Nj, is the value at the r[th] node in the j[th] layer in the t[th] training simulation. .

$V_{Jk}(t)$, k = 1, …, NJ, 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}, …, $F_{(J-1)r}$ 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 $\left(\sum_{\ell=1}^{N(j-1)} W_{(j-1)\ell,jr} * V_{(j-1)\ell}(t) + W_{b,jr}\right)$. 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 Ws, we could work through (A2) to (A5) to obtain values for $V_{Jk}(t)$, k = 1, …, NJ. The objective is to set the Ws so that the resulting fitted values for $V_{Jk}(t)$, k = 1, …, NJ minimize (A1). With the optimal Ws, the fitted values for $V_{Jk}(t)$, k = 1, …, NJ, are the NN approximations to the endogenous variables from the CGE model.

References

Britz, W., J. Li and L. Shang (2021), "Combining large-scale sensitivity analysis in computable general equilibrium models with machine learning: an example application to policy supporting the bio-economy", 2021 GTAP Conference paper, available at https://www.gtap.agecon.purdue.edu/uploads/resources/download/10483.pdf .

Dixon, P.B., B.R. Parmenter, John Sutton and D.P. Vincent (1982), *ORANI: A Multisectoral Model of the Australian Economy*, Contributions to Economic Analysis 142, North-Holland Publishing Company, pp. xviii + 372.

Dixon, P.B. and M.T. Rimmer (2013), "Validation in CGE modeling", Chapter 19, pp. 1271-1330 in P.B. Dixon and D.W. Jorgenson (editors) *Handbook of Computable General Equilibrium Modeling*, Elsevier.

Dixon, P.B., M. Jerie, M.T. Rimmer and G. Wittwer (2019), "Rapid assessments of the economic implications of terrorism events using a regional CGE model: creating GRAD-ECAT (**G**eneralized, **R**egional **A**nd **D**ynamic **E**conomic **C**onsequence **A**nalysis **T**ool)", chapter 6, pp. 121-161, in Okuyama, Y. and A. Rose (eds.), *Advances in Spatial and Economic Modeling of Disaster Impacts*, Springer Nature, Switzerland.

Dixon, P.B, M.T. Rimmer and F. Schiffmann (2024), "Neural-Network approximation of reduced forms for CGE models explained by elementary examples", *CoPS Working Paper,* G-348, November, pp. 18, available at https://www.copsmodels.com/elecpapr/g-348.htm .

Gogas, P. and T. Papadimitrou (2021), "Machine learning in economics and finance", *Computational Economics*, vol. 57, pp. 1-4.

Jin, D., J. Hedtrich and C. Henning (2018), "Applying metamodeling for extended CGE-modeling: Sampling techniques and potential application", *Working Papers of Agricultural Policy, No. WP2018-03*, Kiel University, Department of Agricultural Economics, Chair of Agricultural Policy, Kiel, https://nbn-resolving.de/urn:nbn:de:gbv:8-publ-22648

Horridge, J.M., J. Madden and G Wittwer (2005), "Using a highly disaggregated multi-regional single country model to analyze the impacts of the 2002-03 drought on Australia", *Journal of Policy Modeling*, vol 27, pp. 285-308.

Horridge J.M., Jerie M., Mustakinov D. & Schiffmann F. (2018), ***GEMPACK manual***, GEMPACK Software, ISBN 978-1-921654-34-3 available at https://www.copsmodels.com/gpdoc.htm .

Rose, A., F. Prager, Z. Chen, and S. Chatterjee (2017), *Economic Consequence Analysis of Disasters: The E-CAT Software Tool*, Singapore, Springer.

Wittwer, G., editor (2017), *Multi-regional dynamic general equilibrium modelling of the U.S. economy: USAGE-TERM Development and applications*, Springer, Switzerland.

Wittwer, G, (2024), "The economic impacts of a hypothetical foot and mouth disease outbreak in Australia", *Australian Journal of Agricultural and Resource Economics* 68(1):23- 43, available at: https://onlinelibrary.wiley.com/doi/full/10.1111/1467-8489.12546 .

Wittwer, G. and Horridge, M. (2018), “Prefectural Representation of the Regions of China in a Bottom-up CGE Model: SinoTERM365”, *Journal of Global Economic Analysis*, 3(2), pp. 178- 213.