The spatial economics of energy justice: modelling the trade impacts of increased transport costs in a low carbon transition and the implications for UK regional inequality

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A B S T R A C T

Spatial economic change is an energy justice issue (Bouzarovski and Simcock, 2017) - an essential consideration in how we choose to re-wire the economy for a carbon-free future. Nothing like the conscious system-wide change required has been attempted before. Rapid policy decisions risk embedding existing injustices or creating new ones unless steps are taken to ameliorate those risks. We present a model that takes a whole-system view of the UK spatial economy, examining how increasing distance costs (e.g. through fuel tax hikes) have unequal impacts on regions and sectors. The model establishes an important carbon transition policy principle: change in spatial flows of internal trade, which are certain to occur rapidly during transition, have measurable energy justice implications. Peripheral economic regions, in rural and coastal areas and many city outskirts are most vulnerable, as are petrochemical, agricultural and connected sectors. Policy must go beyond identifying places and sectors most affected: it is the *connections* between them that matter most. The "push" of spatially aware fiscal policy needs to be combined with the "pull" of targeted interventions designed to promote low-carbon intermediate connections. This is not only just, but would help make (potentially costly) transition more politically acceptable.

1. Introduction

The UK economy is a network with millions of physical connections - goods moving between production sites, working their way from primary processing through to final production and sale, often back and forth across national boundaries. This system is first and foremost *spatial*. Over time, political, economic and technological forces constantly push it into new, often spatially unequal, formations. Winners and losers can and do change geographical position as those forces play out.

While these dynamics have always been central to spatial economics, the implications of carbon transition require a comprehensive shift in thinking. Taking the science of climate change seriously implies a rapid move away from fossil fuels. Existing infrastructure and institutions are embedded in a fossil fuel world - changing this will require much more radical action than is commonly accepted (Anderson and Bows, 2012). An energy revolution needs to take place (Jefferson, 2008; Kramer and

Haigh, 2009). The necessity of this is starting to make its way into national policy (Committee on Climate Change, 2019) - but the spatial implications remain little understood.

Without careful policy, this revolution may create new inequalities. This realisation has led to the emergence of ideas about *energy justice* (McCauley et al., 2019) and *just transition* (Heffron and McCauley, 2018), building on earlier environmental justice work. Thinking about spatial injustice is far from new (e.g. Harvey, 1973) but the urgency of transition changes its nature fundamentally (Bouzarovski and Simcock, 2017).

The 'UK 2070' Commission on regional inequalities has recognised how closely climate and spatial inequality are connected (UK 2070 Commission, 2019, p. 22) but there is still a gap in understanding about the scale of the spatial challenge: nothing like the kind of conscious system-wide change required has been attempted before. Because of this, energy justice is all the more imperative. Rapid policy decisions are likely to risk creating new sets of spatial winners and losers, embedding

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existing injustices or creating new ones, unless steps are taken to ameliorate these unintended consequences.

Understanding the processes that potentially lead to spatially unjust effects is a necessary first step in learning how to address them. This paper proposes taking a step back from the detail to focus on a 'whole systems' view of the web of trade connections that constitute a spatial economy. This is in line with current policy emphasis on considering national trade and infrastructure in "a way that more consistently considers interdependencies" (HM Government, 2017).

Specifically, we focus on the impact of *distance cost change* at the national level, as a way to analyse system-wide change. Our modelling approach takes the UK's existing spatial economic layout - the location of firms, their turnover and money flows between sectors - and examines how those money flows change across a sweep of distance cost scenarios that bound likely present-day values. The difference between each increase in distance cost is treated as an 'if-then' scenario, focusing on trade/money flow changes while keeping the spatial economic layout otherwise fixed.

Modelling these broad distance cost changes is meant primarily to open up discussion about whole-system spatial impacts. By keeping the underlying distance model relatively simple, the model asks: even in scenarios where distance costs change evenly, do such cost changes create spatially uneven outcomes? The answer is yes. In terms of transition, a distance cost increase may represent any number of infrastructure and transport policy choices, including most obviously an increase in fuel duty. The model helps think about *where* and *in what sectors* the largest effects of transition cost changes are likely to fall – and thus suggests avenues for thinking about non-regressive policy responses.

Energy justice tends to consider final or domestic energy issues more often. This paper's model shows that higher-level change in intermediate trade flows also have vital energy justice implications. Our approach makes it possible to identify those sectors and places where impacts are likely to be consistent, those more affected at particular distance cost steps and others that change from gaining to losing out (or vice versa) over the full range of model values.

The energy justice literature is methodologically very rich. The model presented here provides a novel contribution to that, while also promoting the idea that such quantitative approaches can be a vital part of the energy justice toolkit.

The model uses three key data sources. UK transport data is used to identify the UK's existing pattern of internal trade distance decay - an essential starting point for the analysis, demonstrating the existence and curve of sub-national distance costs. By itself, spatially collating this data demonstrates distance matters for the UK's spatial economy - the model examines how much it matters, and in which sectors and places it matters most. We also use the UK Business Structure Database, a rich micro-dataset on trade location and composition and a unique source for examining trade interdependencies. This is connected with (non-spatial) trade flow data.

Section 3 describes these datasets in detail and thoroughly documents the model's method. Section 4 presents the results. The conclusion (section 5) synthesises findings from the results and discusses the policy implications in depth. First, we briefly explore the relevant theory.

2. Theoretical context

McCauley et al. (2019 p.919) see energy justice as a set of tools for doing three things: "understanding when and where ethical questions on energy appear, who should be involved in their resolution and ultimately which solutions must be pursued to achieve a sustainable energy system underpinned by fairness and equity".

This paper focuses on the first of these: it aims to identify where, and in what sectors, tensions may appear if pressure is put on the UK spatial economy as a whole. This is then used to examine the underlying energy justice issues. The model also suggests ways to think about the third point: what solutions may best meet just energy outcomes?

Following Bouzarovski and Simcock (2017), we agree that we cannot fully understand energy justice and transition issues without addressing their inherently *spatial* nature. As they say, "energy transitions are generators of geographically uneven social, political, and environmental displacements which may increase the vulnerability of particular social groups or places" (Bouzarovski and Simcock, 2017 p.645). Such change has vital implications for all components of the economy: the location of jobs, the pull factors affecting migration and the spatial provision of services required by workers and their families (such as housing and social services) as well as resource demand and environmental impacts. Addressing energy justice thus requires "interventions in the fundamental driving forces of spatial inequality" (*ibid.* p.640).

Unlike the environmental justice literature it originates from, there are few quantitative takes on energy justice (and some scepticism about certain quantitative approaches; e.g. Heffron et al., 2015). We believe a utility-based spatial economic modelling approach can shed light on energy justice issues and allow us to simulate the ramifications of particular policy scenarios in a way that would otherwise be difficult.

Utility-based methods are highly effective for understanding how cost changes affect whole systems. They see the spatial economy as an optimised landscape, balanced between a set of economic and geographical forces (and, as Fujita notes, equally powerful social forces often left out of the picture; Fujita, 1999, p. 380). That optimum is never perfect or static: over time as economic forces, technology and policy shift, so do geographical winners and losers.

Most importantly, an *economically* optimal landscape is not necessarily *socially* optimal or just. Modelling change in those optima can support energy justice goals by suggesting places to look for negative impacts that policy can then address.

Such an approach allows a 'whole systems' focus - something energy justice theorists embrace (Bouzarovski and Simcock, 2017 p.641; McCauley et al., 2013). It is an old idea (Isard discusses the need to consider the 'gestalt whole' of the spatial economy; Isard, 1956, p. 56) made newly relevant by the urgency of transition.

Concentrating on generic 'distance costs' is a useful tool for whole-systems thinking. It is not a replacement for more specific analyses, but it allows a broader overview that would otherwise be difficult. Distance costs become a much more urgent factor to understand because transitioning to a low carbon economy - if done successfully - is a radical break in spatial economic history. This is why energy justice and spatial economics are such a timely fit. Up to now, spatial economics has existed in a world of gradualism (Pearson and Foxon, 2012) where, for example, oil infrastructure took "as long as a century to work through" (Hall, 1993), ever-declining costs, and a partially blind mix of planning and organic growth - what Fujita et al. (2001, p. 253) call the 'history of the world part one'. For some, the logical conclusion of this is to dismiss the need to factor in distance costs at all, since in modern times they are such a small percentage of overall costs (e.g. Glaeser and Kohlhase, 2004).

The issue is not simply that costs may rise - it is the nature of the required change. A close historical comparison might be containerisation (Stahlbock and Voss, 2008; Hummels, 2001; Taggart, 1999): in this case, a single technology that rapidly *lowered* costs re-oriented the pressure on nations and cities, changing which grew and shrank. Transition implies an even more rapid shift, covering all sectors of the economy - the spatial economic trajectory will be difficult to predict, with path dependencies quickly becoming locked in (Intergovernmental Panel on Climate Change, 2015). Accounting for the energy justice implications of this will need ongoing vigilance.

Much recent transition literature finds lessons in 'shocks' like the seventies oil crisis (National Economic Development Office, 1974; Segal, 2011) or economic cliff edges such as Cuba's adaptation to a sudden halt to oil supply (see e.g. Wright, 2008). These have become examples for intense study and even, in the case of the transition movement, imitation (see e.g. Glasmeier, 2007; North, 2010). But these often have narrow

views of distance costs, both in their focus on raw fuel and view of economic connections.

Our concept of distance costs is used to stand in for the full range of factors that may cause trade friction over space. This is similar to 'trade costs': "the sum of all costs incurred to deliver a good to its user" (Duranton and Storper, 2005, 2008). Transport costs are only one element of this (Disdier and Head, 2008). In the international trade literature (where the idea of trade costs originates) the full range of these elements can include "policy barriers, information costs, contract enforcement costs, … legal and regulatory costs, and local distribution costs" (Anderson and Wincoop, 2003 p.691). In addition, raw transportation costs are themselves composed of other elements. In one U.S. analysis, freight costs are found to be approximately a third fuel, a third driver costs (Fender and Pierce, 2012) - the UK is very similar, despite quite different fuel costs (Freight Transport Association, 2015). Trade costs are deduced from the 'revealed preference' of spatial decay of goods over distance. In our model, UK transport data serves this purpose (section 3.1).

We prefer the term 'distance costs' as many of the international elements are weaker at the sub-national level - but the key idea that these costs are composed of many forces is essential for thinking about the model, and any possible policy response.

Excluding distance has implications for policy goals such as achieving socially just carbon taxes. Fuel taxes in particular clearly have huge importance - Sterner argues persuasively for their role in carbon policy (Sterner, 2012) and shows how OECD countries could have 44% lower transport carbon emissions if they had long-term fuel tax similar that of the UK. Conversely, they could have been 30% higher if American fuel tax levels had been in place (Sterner, 2007). But calculations for creating either revenue-neutral or non-regressive (Leahy et al., 2009) carbon taxes are on the whole aspatial; if changing fuel costs impacts on *distance* costs, any tax change will alter spatial economic output in unpredictable ways. Blanket carbon tax increases that raise distance costs may affect peripheral regions more severely than central ones. Identifying *how* those impacts might fall spatially requires understanding how spatial economies may change form as costs change - this paper is a contribution to that aim.

This section ends with a quick note on ways in which the Business Structure Database has been used by others to analyse the UK's spatial economy. Duranton and Overman's analysis of UK industrial clustering is especially relevant, identifying the UK's pattern of uneven spatial forces. They found at smaller sub-regional scales, same-industry clustering dominates, with most of this below a 50km range (Duranton and Overman, 2005), while between regions (above 150km) they find strong evidence for vertically-linked trade flows between connected sectors (Duranton and Overman, 2008). Other analyses find evidence for functional clustering - HQs and research/development operations clustering more; less human-capital intensive production being more dispersed (Bade et al., 2015).

The BSD has also been used to measure business growth and its affect on employment and innovation over time (Anyadike-Danes et al., 2009; Mason et al., 2009), to examine agglomeration (Simpson, 2007) and a detailed breakdown of the industrial structure of the UK (Bonner et al., 2013).

These analyses contribute to a picture of a dense, optimised UK spatial economy. Our model asks how this optimum may come under stress as costs change rapidly. The conclusion discusses dynamic outcomes in light of the results.

3. Model method and data

3.1. Data

The analysis builds on three data sources from the same year, linked to create an estimate of the spatial pattern of trade flows within the UK. The most important of these is the Business Structure Database (BSD)

(UK Data Service, 2010). This provides an unparalleled description of the spatial structure of the UK economy: the vast majority of individual businesses and productive units are detailed, covering around 99% of total turnover (Office For National Statistics, 2006). It gives information on their exact location, turnover, employee number and 2007 Standard Industrial Classification (SIC) sectoral code at the five digit level. The BSD is managed by the Secure Data Service and must be accessed under secure conditions.

The flow of trade between sectors in the UK is described in 'supply-and-use' input-output (IO) matrices. These matrices give the full network of money flows between sectors (given as 3-digit SIC codes) providing a window onto the morphology of internal trade. Specifically, this paper uses the 'domestic use' input-output matrix, as this gives purely internal trade flows within the UK, excluding imports (Office For National Statistics, 2010). This describes over 7000 flows between sectors for the year we examine.

In this paper, the BSD is linked to the domestic use matrix by SIC code, using the spatial information in the BSD to estimate where trade flows between sectors in the matrix originate and where it moves to when spent. As the most recent domestic use matrix data at the time of the project was from 2010, data from the BSD for the same year is used.

The third data source is Department for Transport (DfT) data for 'goods lifted' within the UK in 2010 (Department for Transport, 2010). Here, we extract regional flows from this data to produce an estimate of the spatial decay of trade over distance. This estimate is then used to calibrate the link between the BSD and the trade flow matrix to create a range of 'if-then' scenarios for how trade flows spatially within the UK. This dataset demonstrates an essential fact: trade decays over distance quite rapidly for domestic intermediate goods, much more-so than would be expected if trades were between random locations on the island of Great Britain (see supplementary material point 4).

3.2. Overview of the method

The analysis starts by estimating *where* geographically in the UK each sector's consumption originates. We label the supply-use IO matrix as **M**. Each element of **M** describes a money flow m_{od} between an origin sector (*o*) and destination sector (*d*) - for example, money originating from 'fabricated metal products' going to 'basic iron and steel'. **M** is non-spatial: each m_{od} value is for money flows between different sectors in the UK as a whole.

To create a spatial estimate for where each flow originates, each m_{od} is split across the UK's 243 'travel to work area' (TTWA) zones (Coombes and Bond, 2007). We index these spatial locations using $z = 1, 2, … 243$. Every m_{od} value is split using a proxy for demand: turnover from the BSD. The BSD's 700-plus SIC codes are binned into the cruder three-digit categories used in the domestic use data so the two data sources match. v_{oz} is turnover summed per origin sector and zone. Let $\widehat{m}_{oz}$ be the geographical proxy. $\widehat{m}_{oz}$ is just a fraction: each origin sector's local turnover in zone z divided by that sector's national turnover, giving individual proxy values that sum to one for each origin sector across all zones:

$$\widehat{m}_{oz} = \frac{v_{oz}}{\sum_{z=1}^{243} v_{oz}}, \; where \; 0 \leq \widehat{m}_{odz} \leq 1 \tag{1}$$

Each proxy fraction $\widehat{m}_{oz}$ is then used to split each IO matrix cell m_{od} geographically, giving each origin 'budget' y_{odz} that e.g. construction in London spends on fabricated metal across the entire UK:

$$y_{odz} = m_{od} * \widehat{m}_{oz} \tag{2}$$

This creates over four hundred thousand separate chunks of consumption, one for each matrix cell split across each TTWA. (Not all TTWAs contain all sectors - on average, they contain 41 out of a possible 58.)

Each budget y_{odz} is then 'spent' using a constrained Constant

Elasticity of Substitution (CES) function (see section 3.3), allocating them from their origin zone assignments to TTWAs containing the destination sectors, creating a spatial estimate for all IO matrix flows.

This process is repeated across a 'parameter-sweep' of distance cost steps that bracket likely real-world values (see section 3.4). y_{odz} does not change on each step as this is based on the fixed turnover proxy - it is differences in patterns of destination spending between distance costs steps that the analysis uses. The results ask: how does spatial spending *change* between steps across sectors and places?

There are two other important considerations. Firstly: before turnover from the BSD is assigned to sectors/zones to make the origin proxy, it is split between a firm's local units (related branches, production sites and other business premises) in proportion to each unit's employee count. The vast majority of records in the BSD are single-unit - these make up about 97% of all enterprises by number but only 40% of total turnover. The remaining 3% of firms with more than one unit thus account for 60% of turnover. Multi-unit firms are usually spread over more than one TTWA and units' SIC codes can vary. Splitting turnover thus assigns it correctly to sector and location.

Secondly, trade flows for physical goods sectors only are examined. These are the first 58 SIC categories. Turnover in physical goods sectors from the BSD much more closely match sector flows in the domestic use matrix, making for a better initial use of the method. (The turnover proxy correlates well to consumption in the domestic use matrix when focusing on physical goods only: an r^2 of 0.94.) The conclusion discusses extending the method into services.

3.3. Distance decay model

The distance decay model takes each estimate of sectoral/geographical consumption y_{odz} and 'spends' it across the UK to produce a demand map. To do this, each origin sector/zone (where e.g. 'fabricated metal products' in London is one sector/zone) is treated as a separate economic 'representative agent' with a budget y_{odz}, where d is the sector they buy from across the whole UK. A constrained function, keeping values to those in the IO matrix, is used to allot that agent's budget across the UK. A 'Constant Elasticity of Substitution' (CES) function is used for this purpose. The CES approach has been used successfully at a more aggregate level to produce analyses of international trade costs (Anderson and van Wincoop, 2003, 2004).

The intuition for the CES function is this: a range of production sites within a particular geographical zone can buy a mix of inputs from across the UK. First, this mix will have a certain spatial decay pattern. Collectively, firms will likely buy less from more distant sites if a closer opportunity exists. Buying patterns for a group of firms will tend to look more like a smooth spatial decay, compared to a single firm. Second, this pattern will be affected by input substitutability. Firms buying a highly substitutable input like cement will be more likely to buy from the closest source. For more specialised or valuable inputs, geography will matter less. The CES function captures this dynamic by letting a single representative agent buy from across the UK.

The method uses its own form of CES function that turns a representation of individual trades into an aggregate picture of spatial spending. Each individual trade between sectors is represented by a simple cost equation:

$$p_{odz} = \alpha + \beta n_{dw} \qquad (3)$$

p_{odz} is the total price an origin sector o in zone z faces for a unit of good from destination sector d. α is the base cost of the good, β is the per-unit distance cost (these do not vary; see below). n_{dw} is the distance from the origin sector/zone in z to the location of each zone containing a destination sector d. The location of these destination sector/zones is indexed with $w = 1, 2, \dots 243$. By representing each individual trade, it would be straightforward to use more involved distance functions such as economies of scale or zoning. The paper sticks to this simple equation,

however - it allows a consistent fit with the spatial decay data (see next section) and is also the most transparent way to test the effect of distance cost change in the method.

Each individual purchase is entered into a CES function defined in the following way:

$$g_{dw} = \widehat{m}_{dw} * P_{odw} \frac{P_{odw}^{(1/\rho-1)} * y_{odz}}{\sum_{v=1}^{n} \widehat{m}_{dv} * (P_{odv}^{(\rho/\rho-1)})} \qquad (4)$$

y_{odz} is the budget described in section 3.2 being spent in zone z by origin sector o (in z) on destination sector d (across all zones the UK). w is the specific destination zone being calculated for. $v = 1,2, \dots 243$ is the set of *all* zones containing the destination sector d. g_{dw} is the individual money amount going to sector d in zone w. Each destination sector/zone amount g_{dw} is calculated individually in turn, creating a set of constrained spends for each y_{odz}. p_{odw} is equation(3): the cost of buying from a specific destination sector/zone; p_{odv} is the cost for every other destination sector/zone for this budget.

Every individual spend g is then summed per destination sector d and TTWA w to give a final assigned demand map. The results then use the difference between these demand maps at each increase in distance cost β (see below) to estimate how spending demand changes as distance costs change.

A key element of the function is $\widehat{m}_{dw/dv}$ – these are the relative size of each sector receiving money. It acts to multiply each individual trade to their sector scale. The turnover proxy is used again for this purpose, allowing the relative size of individual sector/zones to be entered into the CES function.

ρ is the elasticity of substitution parameter. At high values ($\rho \to 1$), a sector is buying more generic inputs, preferring the cheapest available suppliers. If ρ is low, a sector buys a more diverse mix from a larger geographical spread. At the firm level, this implies the need for more specific forms of input.

3.4. Determining model values

A set of model parameter values are selected that bound the spatial decay of UK industrial trade, matching against the Department for Transport data. The whole range is then parameter-swept (see e.g. Wibisono et al., 2008). β is increased in steps, representing a series of increasing distance costs. The bound of this range is within the solid lines in Fig. 1.

There are three parameters that must be set in the model. First, the elasticity of substitution parameter ρ, which shapes the mix of goods bought, and thus the distance they will be bought from, is used in the CES function itself. Second, value density (Lovell et al., 2005) is used. In terms of the model, this can be defined as the ratio of base good cost α over per-unit distance cost β. The important spatial idea embodied in value density is that neither raw value or distance cost alone determines the distance at which goods can viably trade - the ratio determines it. For α/β, this holds true. Thus, when setting parameters, this means there is only actually one number to target rather than two. Finally, a target total transport cost can be used to choose a single pair of values for ρ and value density - this is explained below.

Fig. 1 summarises these key elements used for calibration, comparing actual transport data with the model's distance decay. It contains the following elements. The three solid lines show how the underlying distance decay model works. These show three different values for distance cost, with the centre value being a 'most likely' estimate matching data, and the two outer lines setting bounds for the model's parameter sweep. The upper line labelled 'low distance cost' shows spending spread over a much larger distance than the lower-labelled 'high distance cost' line.

Using the method described in section 3.3, Fig. 1 illustrates the distance decay model by simulating a single 'representative agent' at distance zero (representing a group of firms in a particular sector/zone) buying from an evenly spaced range of sectors (three hundred in the case
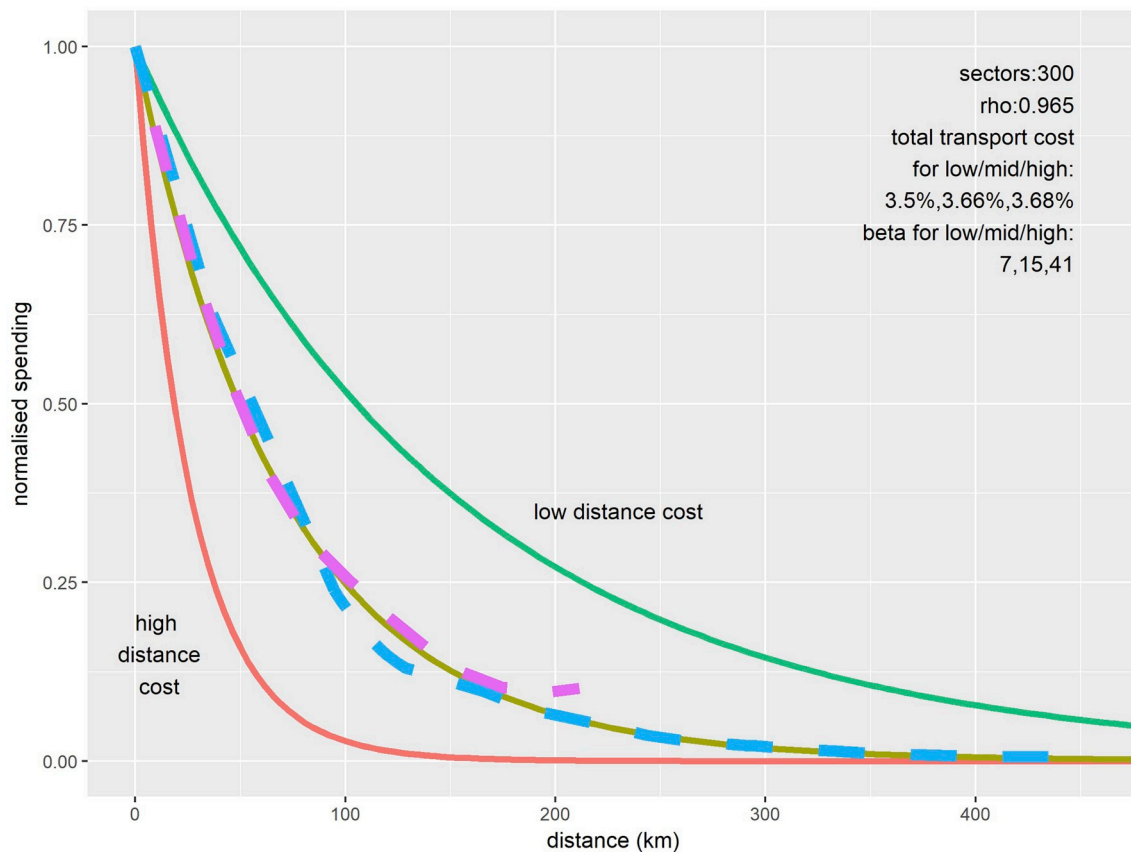
Fig. 1. Summary visualisation of model calibration. Low and high distance cost lines bound all distance cost values used in the model. The central line is a 'most likely' fit to spatial decay of trade from Department of Transport data. Solid lines are model values, the central dashed lines are LOESS curve fits to DfT data.

of Fig. 1) up to a distance of 1150km, the maximum buying distance between TTWAs in the UK. The agent buys a mix of goods over distance, with the spatial decay of the mix determined by ρ and value density. Model output and data are all normalised so that buying at distance zero equals one. A key feature of the CES approach is that the normalised shape of the spatial decay curve remains unaltered by the number and position of sellers (though actual optimal quantities change, shifting the shape up and down).

The dashed lines in Fig. 1 show actual distance decay values deduced from DfT data, consisting of a series of data tables describing road freight activity for Great Britain. Two slightly different sources are used: drop-off of trade between the old Government Office Regions (GOR) and data for distance of 'goods lifted' (actual weight of goods carried over distance) for a range of commodities. Adjusted for 'route factor' difference using Google route data, both sources match (see e.g. Black, 2003; Chapman, 1979 and supplementary material point 3 for method). The central solid line in Fig. 1 is a best-fit LOESS estimate of this data.

3.5. Total transport costs

There are a range of combinations for ρ and value density that produce the same decay of spending over distance. In order to settle on a single pair of values for them, the final constraint used is transport cost as a proportion of total spending. Fig. 1 includes these percent transport costs for each of the test model's lines, ranging between 3.5% and 3.68%. These target values were chosen by extracting an estimate of average transport costs from the 2010 domestic use data and comparing intermediate transport sector consumption against total spending. (These average values are analysed in more depth in supplementary material point 6.).

Transport costs derived from the IO data concur with existing survey-

based estimates of transport costs. Diamond and Spence (1989) found transport costs to be between 3% and 6% of 'total operating costs'. For the U.S., Glaeser and Kohlhase (Glaeser and Kohlhase, 2004) find them to be between 1.2% and 10%, though domestic transport costs are likely to be different for larger land-masses. Here, a single average transport cost value from the domestic use IO data is used - this is 3.66%. In the model, this shifts between 3.5% and 3.68% as total transport costs vary with distance costs, but not monotonically: optimal buying choices are more localised when per-unit transport costs rise, so this reduces relative transport costs (this is the key spatial economic effect of varying value densities).The test model data's 'most likely' spatial decay curve is matched to the mean value of 3.66%, resulting in a high elasticity of substitution ($\rho = 0.965$). A high value density range is used to buffer this 'most likely' value: with base good cost α set to 30,000, β ranges from 7 to 41.

4. Results

4.1. Overview

The results of the model are presented in two ways. Section 4.2 begins by looking at the overall geography of the model output. It then digs deeper into that geography, looking at how specific places are affected, and what sectors in those places are particularly vulnerable. Section 4.3 looks more closely at sectoral impacts, ending with a detailed geographical look at four sectors the prior analysis identifies as most affected.

Where the first section focuses on the impact of distance cost *increases*, the second considers which sectors are 'most affected' by looking at the overall geographical volatility of demand. The last section also shifts the focus from average impacts at all distance cost steps, looking

more closely at how low versus high distance cost changes affect some sectors and places consistently, others variably.

4.2. Geographical effects: overall impact

The maps in Fig. 2 give a spatial overview of the model's results. The amount of demand each TTWA gains or loses on each distance cost increase is averaged for the whole parameter sweep. The two maps compare the *absolute* amount of money change versus *percent* change (between each distance cost increase) in each TTWA. While of the same polarity in each TTWA, the two show quite different geographies. The map of absolute change is best for a 'top down' view of how money flows change for the UK as a whole. London and Aberdeen stand out starkly from all others. London is by far the largest net gainer at all levels of distance cost increase: four times larger gains than the next two largest gainers, Belfast and Glasgow. Aberdeen has the largest absolute losses - the causes of these are discussed below.

Percentage change emphasises instead the point of view of each TTWA: while a small economy, Machynlleth in Wales has a near 5% average drop, Aberdeen - despite being the largest loser in absolute terms - has only an average 0.6% fall. Percentage-wise, Machynlleth is the second most negatively affected; Aberdeen is 132 on that list. Equally, Shetland Islands' 10% gain puts it first in the percentage rank, where London gains only 1%, placing it at 52.

There are thus quite different clusters affected in absolute and percent terms. Large absolute gains are geographically disparate, while the losses are focused in the Midlands. There are percentage gain clusters, however, concentrated in the South-West, Northern Ireland, and North and central Scotland, while the percent losses cluster in North

Wales, the North-West coast and other coastal spots.

4.3. The industrial structure of the least/most affected TTWAs

Do those TTWAs that experience the highest and lowest change in demand as distance costs increase share anything in common, in terms of their industrial structure? To answer this, the UK is divided into four equal-sized groups of TTWAs and the groups are then ranked from 'largest demand gains' to 'largest demand losses'. This section looks at the top and bottom of these four groups.

In order to give both TTWA and sector change an equality across all values, the average of *each TTWA's sector percent change in demand* is used to create the rank. This means, for example, that a TTWA with forty sectors, each gaining 10% more demand over a distance cost increase, will have the same average as a TTWA with ten sectors, if they also each gain 10%. TTWAs like Aberdeen that have been identified as losing large absolute amounts can now appear as overall gainers. In Aberdeen's case, this is because its crude losses are only 4% per beta step on average; many of its other sectors make big gains in percentage terms.

Fig. 3 shows the economic structure of the top and bottom groups (solid bars), mirrored against each other for easy comparison. Percent sector size for the entire UK economy is overlaid on both as hollow bars, to show how they differ from the national picture. Both are ordered by size of sector at the national level; the top thirty of these are given.

There is a clear contrast in industrial structure. Largest-gaining TTWAs are dominated by construction, crude/petrol, petrochemicals and mining support (the solid bars are larger than the hollow bars marking those sectors as a percent of the whole UK economy). In the 'largest losses' group, each of these is much smaller than the national
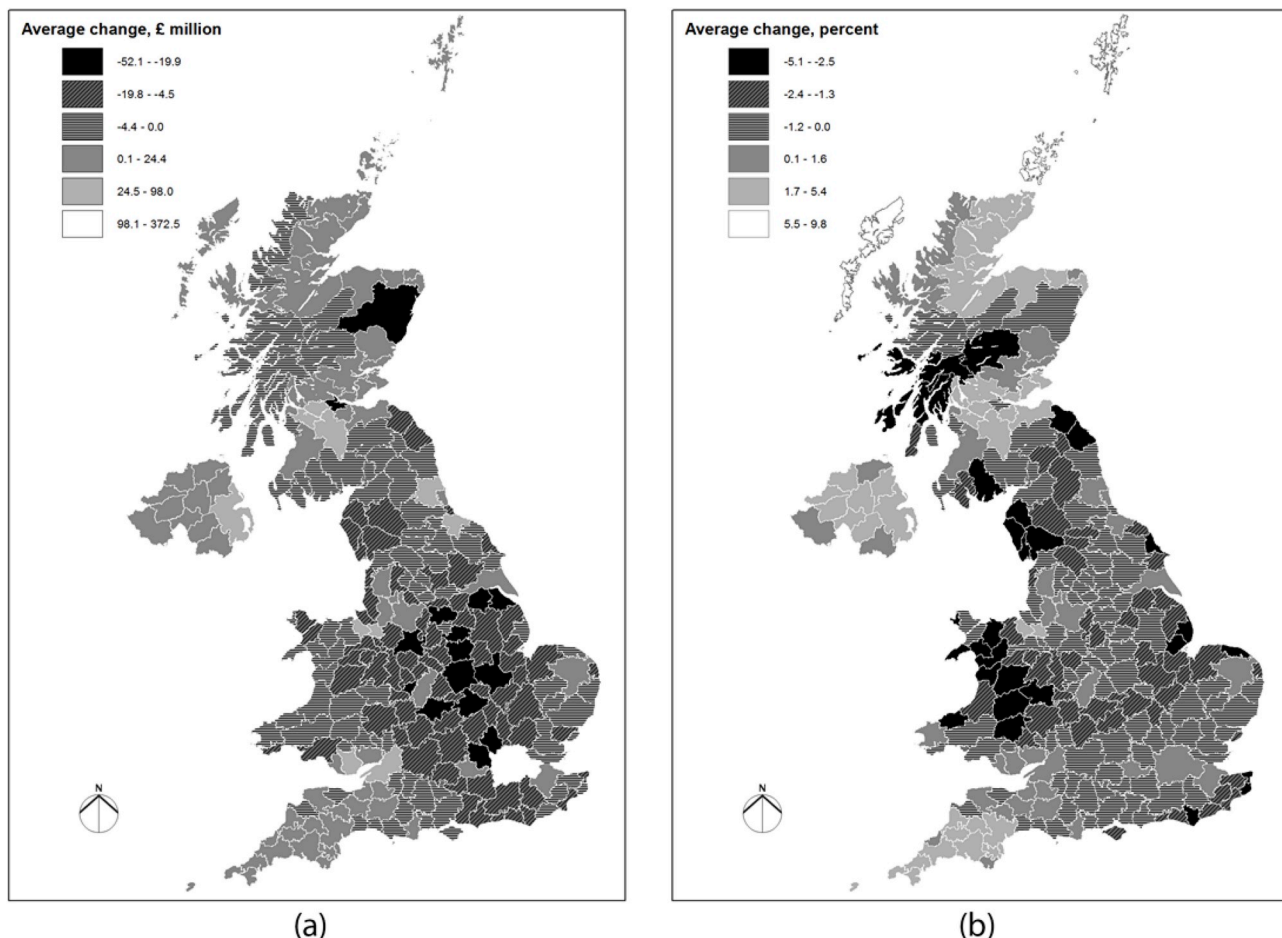

Fig. 2. TTWA average change in demand over whole parameter sweep, absolute (a) and percent (b).
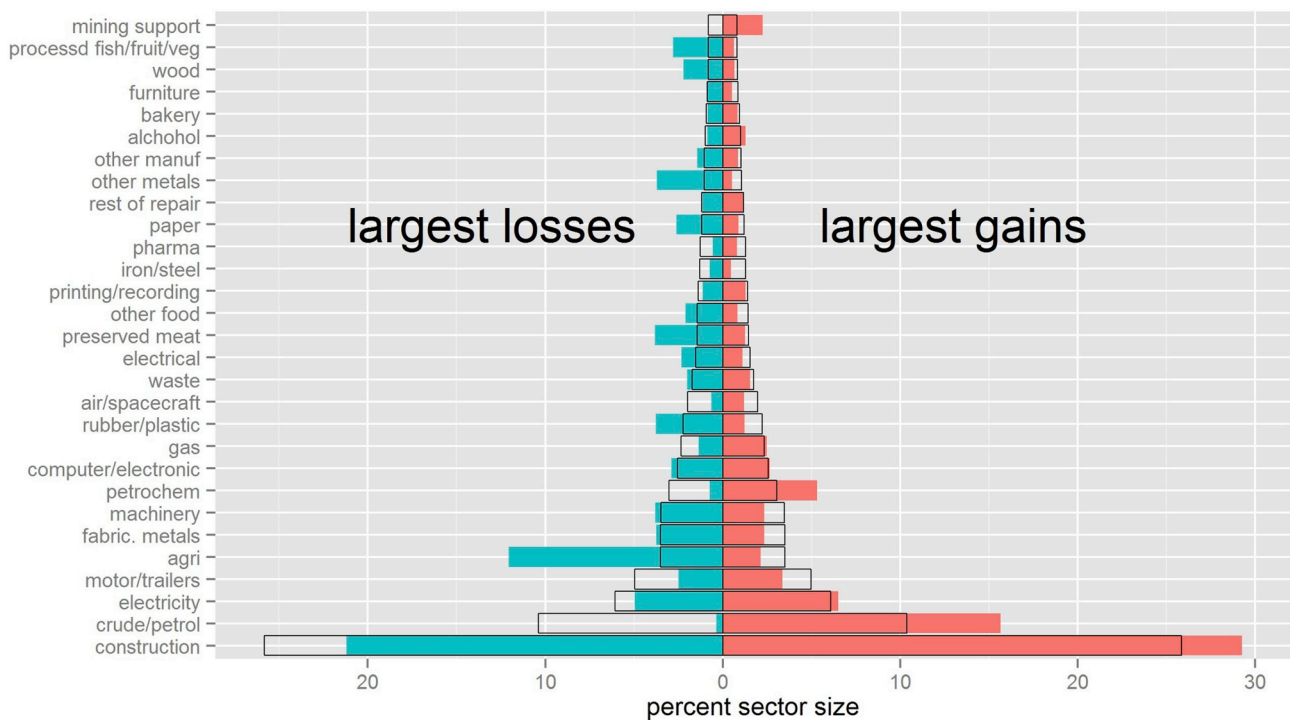
Fig. 3. Economic sector size (as percent of each sub-group's whole economy, measured by turnover) for the 'largest losses' and 'largest gains' TTWA groups. Hollow bars are percent sector size for the UK economy as a whole. Top thirty sectors (of whole economy) shown. (Note: in this figure, 'crude/oil/gas' and 'petrol/coke' have been combined into 'crude/petrol', in order to meet with secure data disclosure requirements.)

picture - in the case of crude/petrol and mining support, they are almost non-existent. The largest-losses group also has a clear agricultural structure: agriculture itself makes up a far larger proportion of its turnover than nationally, and a number of sectors in the agriculture processing chain are over-represented.

4.4. Sector effects 1: which sectors are most affected by distance cost increase?

This section identifies the sectors most and least affected by distance cost change across the parameter sweep by examining the *geographical volatility* of demand. Because total demand *per sector* does not change (it is fixed to the original input-output matrix row sums) raw demand cannot be used to measure sector impact. However, the difference in *where* the method assigns this demand between distance cost steps can be used. The absolute maximum change for a given distance cost increase would arise if all demand moved from one subset of TTWAs to another entirely separate subset - a hundred percent change (this is always symmetrical, negative and positive change summing to zero). Thus, smaller changes can be made proportional to this hundred percent maximum for each sector. This makes change comparable across otherwise disparate sector sizes: the higher the percentage, the more geographically volatile that sector's response is. (In absolute terms, sectors that see the largest movement of money are, unsurprisingly, those with the largest total demand. This correlation is almost perfect; a Spearman correlation of total sector demand versus average per-sector demand *change* over the sweep is 0.98).

To make sector response also comparable across distance cost values, each can be ranked for every parameter step, where first-ranking is highest-percentage ('most affected') and last is smallest. Sectors with a low standard deviation (SD) of their ranking over the whole parameter sweep have the most stable response to distance cost increases. High SD sectors change their rank position - the impact of distance cost change is more variable.

Fig. 4 picks out fifteen of the least and most affected sectors, judged

by their average position in the rankings over the whole parameter sweep, and where rank 1 is 'most affected'. Their standard deviation is shown by circle size, indicating which change ranking position more than others over the full range of distance cost change.

Coastal sectors are most affected, both highest in the rankings and with small standard deviations, so they stay close to most-affected overall. Crude oil and petrochemicals also both tend to locate in coastal regions - and most of the other high-ranking sectors rely on petro-chemical input. Inorganics, for example, includes manufacture of fertiliser and nitrogen, which requires natural gas input; a number of other high-ranking sectors are agro-chemical and feed related. Petrochemical production processes tend to be highly geographically clustered; this result seems to suggest these will come under particular pressure. (The geography of two of these sectors is examined below.) A number of primary-production and low value-density sectors appear to be the most affected also: cement/lime/plaster, coal/lignite and iron/steel.

4.5. Sector effects 2: geographies for four key sectors

These final results focus on how demand in four key sectors changes geographically over the full sweep of distance costs. Two are petrochemical-related: crude/gas/ore and inorganics. Another two - construction and fabricated metals - see the largest absolute shifts in money amounts between TTWAs. (The figures in this section are best viewed in colour.)

Fig. 5a illustrates the approach used by showing how demand for crude/gas/ore changes in all TTWAs receiving demand. Gains and losses are symmetrical each side of zero, as per the previous section, balancing the input-output table row sums on each step. The most prominent TTWAs are picked out in the legend. London, in light blue, begins with the largest gain, but ends with the largest loss - it can be seen in top left and also bottom right. Aberdeen's losses completely dominate for the lower half of the parameter sweep but then become insignificant in the higher-cost half. Middlesborough gains well past the 'most likely' β
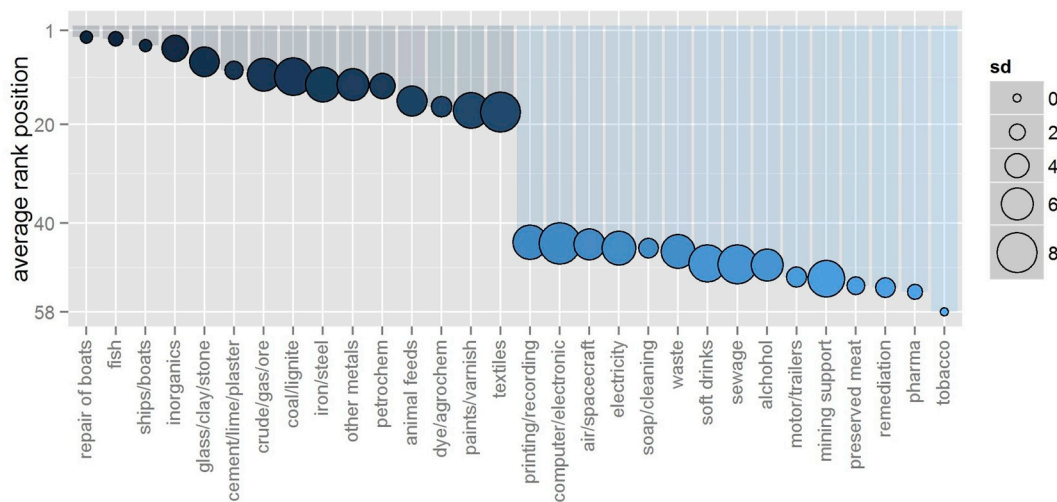
Fig. 4. 'Most affected' sector rank, average rank for whole run, top and bottom fifteen. Circle size indicates standard deviation of rank position across the whole parameter sweep.
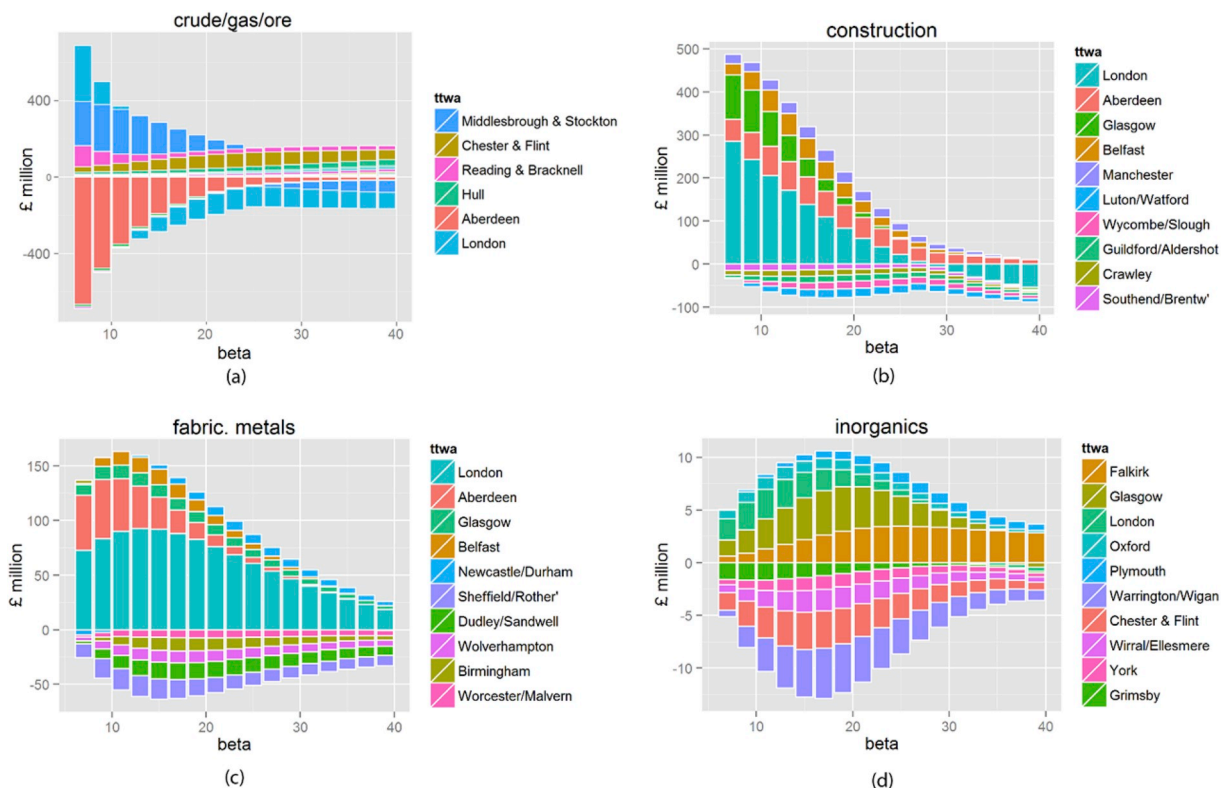

Fig. 5. Four top 'most affected' sectors by total demand change. Change for top 5 gaining/losing TTWAs across the parameter sweep.

change value of 15. Chester, Hull and Reading are the only TTWAs to gain for every step.

Fig. 5b and c plot only the top five gaining (top half of legend) and losing (bottom half of legend) TTWAs for each sector - so they are not symmetrical. For construction and fabricated metals, London dominates the story, taking the majority of gained demand, though in construction it turns to losses at very high distance costs. For these three sectors, it is the larger cities that tend to gain with the regional centres losing - Sheffield in particular sees a large loss in demand for fabricated metals as distance costs increase.

Inorganics - along with other coastal sectors - does not have the largest absolute losses but sees big movements of demand relative to its

size. A comparison of Falkirk and Glasgow inorganics shows how a place's response can be very different as distance costs increase. At lower values, Falkirk's gains are small - it appears to benefit consistently only in the higher value range. Glasgow, conversely, sees its gains peak and then drop away, turning to losses right at the top of the range. Inorganics has a strong tendency to cluster near coastal petrochemical production, especially around Wirral/Ellesmere. Its existing clusters tend to lose out as distance costs increase. It sees its biggest positive shift to Falkirk, another petrochemical centre. Wirral/Ellesmere suffers consistent losses, along with nearby Chester. The pattern for inorganics is markedly consistent: losers lose and gainers gain right across the sweep.

5. Conclusion and policy implications

This paper has analysed how changes in distance costs impact on money flows between UK economic sectors and places. The model is a series of if/then scenarios grounded in the data, bounded by plausible distance cost values. It links the spatial pattern of industries to an input/output table of flows *between* these industries, offering a way to theorise about the spatial forces connecting them - and then to examine how spatial economic *change* may impact places and sectors unequally.

Next, we provide a synthesis of the results before analysing their policy and energy justice implications.

For some sectors and places, change is consistent across all distance cost values. For others, increases for the lower values show quite different and sometimes opposite results, meaning the outcome is more dependent on whether the low or high distance cost scenarios more closely match reality. In the four key sector results (section 4.5) for example, London loses demand in the 'higher' scenarios for some key sectors like construction, in contrast to its usual pattern of gains. Other sectors like fabricated metals and inorganics generally show consistent responses, though inorganics also shows - for Falkirk and Glasgow - how positive demand changes could be very different depending on which scenario applies.

Many major cities see demand increase on average as distance costs increase - for instance, Birmingham, Manchester, Bristol, Glasgow and especially London (Sheffield and Leeds buck this trend with slight drops). This is mirrored by drops in demand from TTWAs neighbouring these cities. A swathe of the South loses demand to London and a few other key centres.

Though not large economies in absolute terms, agricultural areas generally lose demand, with knock-on effects for food production chains showing up in the largest loss/gain analysis and the sectoral volatility ranking. Indeed, the most striking loss of demand, percent-wise, is in agricultural parts of Wales. This is matched only by a few select coastal zones.

There is an overlap of coastal impacts with (largely coastal) petrochemical sectors and their vertical linkages. Each set of results shows this in different ways, with the volatility ranking particularly suggesting that coastal petrochemical supply chains are vulnerable. A low-carbon spatial economy would obviously have particularly stark implications for the petrochemical sector but these results highlight how these could cascade to its very strong spatial and sectoral linkages, further weakening coastal peripheries. (This is without considering the macroeconomic implications; cf. National Economic Development Office, 1974.)

These results support an important transition policy principle: change in the spatial flows of internal trade, which are certain to occur rapidly during transition, have measurable energy justice implications. In the UK, already vulnerable parts of the economy appear most at risk.

The most essential policy and energy justice implications are clear: the *spatial* impact of fuel duty or other carbon taxes are more important than usually understood. If unaccounted for, regressive impacts may result. Sterner's work (discussed in section 2) clearly shows how important fuel taxes can be for carbon output, but it is equally clear from the model that blanket cost increases will hit already peripheral areas more heavily - rural, agricultural and coastal regions and, less-so, city outskirts.

Increasing distance costs is spatially contracting: trade pulls in. Regions may benefit if they are economically strong already, or if the contracting trade happens to fall more heavily where they are. Note that the same applies when distance costs *drop*: the existing spatial morphology will be equally put under pressure.

So, simply targeting those places that are made worse off presents difficulties: it is the *connections* between places and sectors that matter. A policy like targeted fuel duty could address this by allowing the hardest-hit cheaper access to necessary inputs (differential fuel duty is an established idea - in the UK, red diesel is taxed at a much lower rate) but this will not solve the underlying economic damage. Regional targeting will work better if the focus is on developing economic/trade connections, especially to related regions and sectors that may be struggling as transition bites. As the first UK2070 report makes clear, "levels of connectivity are still dominated by the inherited London-centric networks" (UK 2070 Commission, 2019, p. 70). It suggests a need to rebalance. This could be achieved through targeted low-carbon intermediate connections that increase connectivity for more vulnerable regions (which as low carbon, are less exposed to rising fuel duty), either with subsidies or support for specific technology deployment. If fiscal policy is the "push", this is the "pull". The UK Climate Commission has also suggested using sectoral compensation, emission trading allowances, differential tariffs (a form of fiscal policy) and targeted standards (Committee on Climate Change, 2019, p. 29). Consideration should be given to how all these available tools may aid or hinder deeper connectivity, not focusing purely on place or sector based benefits.

All of the policy design implications so far are based on the existing short-run model structure. In the longer-term, dynamic responses become important. Longer-term demand losses are more easily interpreted than gains: *ceteris paribus* loss of capital would lead to contraction and firm closure. Demand *increases* are more complex: they could lead to growth or indicate that a local market simply cannot meet that demand and so the area or sector will suffer. Understanding what these tensions would mean for the dynamic pattern of spatial 're-wiring' as firms adapt (or close) will require a combination of existing spatial economic ideas and an agile analysis of how increases in renewables penetration will alter the economic landscape. Carbon tax costs will partly drive firm location choices (Exbrayat et al., 2015). Climate change itself, of course, impacts on spatial economic outcomes (Desmet and Rossi-Hansberg, 2015). Existing cluster patterns built on substitutability (Berthelon and Freund, 2008; Disdier and Head, 2008), complementary or competitive regional relationships (Overman et al., 2010), labour markets and other forces will interact with transition. A particularly important factor is Krugman's core-periphery dynamic (Krugman, 1991): increasing costs could actually benefit peripheral areas, if they are less connected to an overly dominant core like London, while being better connected with other, similar regions - a goal that would be supported by the "pull" policies mentioned above.

All of these dynamics will be radically affected by renewables penetration policy choices. Three factors in particular will be key: zero-carbon transport, the location of renewable energy infrastructure production and how both of those alter the landscape for the petrochemical sector and its strongly spatial linkages. If transition succeeds, nascent renewable infrastructure clusters (such as Hull's 'Green Port') will usurp petrochemical production. The level of economic disruption this causes will depend partly on policy - petrochemical-intense places could be supported to transition - but also on fundamental differences in supply chain structure and labour supply.

The granularity of detail implied by how renewables penetration interacts with all the spatial forces described above is beyond the reach of our model. Future work could include it more explicitly, to aid thinking on policy design for specific zero-carbon interventions. For example, a more granular version of the model could assess spatial and energy justice effects of zero-carbon transport technologies tailored to specific intermediate industry linkages.

It is unrealistic to expect all implications of every technology to be understood before the fact, but that does not preclude taking a 'walk asking' approach (Jeffries, 2010), monitoring how they impact the spatial layout of the UK over time.

The moral of the model is that energy justice is inherently spatial - and will only become more-so as transition ramps up. The power of the energy justice framework is in understanding that a mixed toolbox is required to make transition just. We hope for a fruitful working relationship between quantitative approaches such as ours and more qualitative methods that can identify ways to work with stakeholders.

There are a number of other avenues for improvement in the model

itself - perhaps starting with disaggregated parameter values. Transport costs (and thus value density) could be made sector-specific, as could elasticity of substitution. As mentioned above, low value-density goods are usually also more substitutable. The interaction of these two could be explored: the link between substitutability and distance naturally arises from the CES function's ρ parameter. The use of turnover as a proxy for demand would benefit from testing alternatives; this is perhaps more true for demand destinations, where gross value added (GVA) or employment levels could also be used to fine-tune sector estimates. Extending the method to include service sectors would likely require a way to integrate labour: the defining characteristic of those sectors is that they are people-intensive. People's distance cost has a direct impact on overall productivity (Rice et al., 2006). The supplementary material (point 8) analyses this issue in more depth.

There are also potentially important extensions by incorporating myopia, asymmetric information and bounded rationality behaviours into the model which can profoundly affect market responses to environmental risks and policies (e.g. Pryce et al., 2011). Finally, some accounting for cross-border flows, if only in a very aggregate sense, could be useful. Relative internal/external trade quantities may offer a way to do this.

Creating a just transition requires working to understand the spatial implications of technological, economic and policy change, identifying places and sectors that may lose out, and striving for policy that can help make (potentially costly) transition more politically acceptable (people value fairness as well as affordability; Demski et al., 2017).

A continued dialogue between the UK's rich data and our understanding of the underlying theory is essential to this (Duranton and Overman, 2008). As the UK works to develop a spatial economy fit for the twenty-first century, transition forces us to re-think our spatial economic toolbox.

Data availability

The article uses three secondary datasets.

- The input-output domestic use data is available at: https://www.ons.gov.uk/economy/nationalaccounts/supplyandusetables/datasets/ukinputoutputanalyticaltablesdetailed
- Department for Transport 'goods lifted' data has changed since used in this paper. The data used here is available at https://github.com/DanOlner/grit. Current goods lifted data is available at: https://www.gov.uk/government/statistical-data-sets/rfs01-goods-lifted-and-distance-hauled
- The Business Structure Database is secure access only. Full details can be found at: https://beta.ukdataservice.ac.uk/datacatalogue/studies/study?id=6697

Data acknowledgement

This work was based on data from the Business Structure Database, produced by the Office for National Statistics (ONS) and supplied by the Secure Data Service at the UK Data Archive. The data are Crown Copyright and reproduced with the permission of the controller of HMSO and Queen's Printer for Scotland. The use of the data in this work does not imply the endorsement of ONS or the Secure Data Service at the UK Data Archive in relation to the interpretation or analysis of the data. This work uses research datasets which may not exactly reproduce National Statistics aggregates.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2020.111378.

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