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LOCAL CONSUMPTION AND TERRITORIAL BASED ACCOUNTING FOR CO_2 EMISSIONS

BY

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Local consumption and territorial based accounting for CO_2 emissions*

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Abstract

We examine the complications involved in attributing emissions at a sub-regional or local level. Specifically, we look at how functional specialisation embedded within the metropolitan area can, via trade between sub-regions, create intra-metropolitan emissions interdependencies; and how this complicates environmental policy implementation in an analogous manner to international trade at the national level. For this purpose we use a 3-region emissions extended input-output model of the Glasgow metropolitan area (2 regions: city and surrounding suburban area) and the rest of Scotland. The model utilises data on commuter flows and household consumption to capture income and consumption flows across sub-regions. This enables a carbon attribution analysis at the sub-regional level, allowing us to shed light on the significant emissions interdependencies that can exist within metropolitan areas.

JEL Codes: H73; Q56; R12; R15.

Keywords: CO_2 emissions; environmental accounting; regional interdependencies; metropolitan areas; commuting.

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1 Introduction

Although the greenhouse gas emission problem is inherently global, local level policies could contribute to its solution. In particular, cities are seen to offer potential for reducing greenhouse gas (GHG) emissions. As Dhakal (2010) points out, economic activity is concentrated in cities and therefore they drive a significant share of overall emissions. However, in most cases, per capita emissions from cities are lower than the average for the countries in which they are located; something which is true of our study area also. Furthermore, emissions vary significantly between metropolitan areas and are associated with local planning policies (Glaeser & Kahn 2010).

This suggests that there is some potential for reducing emissions through the use of local level emission reduction policies, which are tailored to differences in the functional activities of different sub-regions. There is increasing interest in analysing GHG emissions and implementing policies for their reduction at the urban level (Dhakal 2010, Dodman 2009, Parshall et al. 2010, Weisz & Steinberger 2010)[1]. Given the important role cities play in emissions generation, and in order to capitalise on the emissions-reduction potential of cities, city-level carbon budgets have been proposed (Salon et al. 2010).

Conversely, since a lot of GHG emissions are embodied in trade across administrative boundaries, it is not clear ex ante how effective or equitable local level emissions policies will prove. This issue has already received significant attention in the context of trade across nations (Munksgaard & Pedersen 2001, Peters & Hertwich 2006) while at the local level, interregional trade, commuting and shopping trips can have similar effects.

[1]This interest is not just academic, but something that is on the agenda for local governments. For example in the UK, Glasgow City Council both measures its 'carbon footprint', and has a Carbon Management Programme to facilitate reduction in line with stated targets. Similar actions have been taken by various sub-regional entities such as West Sussex County Council and the Lake District National Park Authority (Energy and Climate Change Committee 2012, pp. 14-15).

Therefore, it is important to understand the spatial interdependencies that exist in the composition of the emissions total within regions and nations. Furthermore, the choice of GHG accounting principle that underlies regional, national or local GHG targets can influence the spatial distribution of the required GHG emission reductions.

In order to explore this issue, we use a three sub-region model of Scotland (the regional economy in our case). These are: Glasgow (GLA) (Scotland's largest city), the rest of Strathclyde (RST) (representing the metropolitan areas surrounding Glasgow), and a residual sub-region comprised of the rest of Scotland (ROS). The size and location of each of the three regions is shown in the Map in Figure 1.

Using our three sub-region model, we seek to explore four issues that are important in understanding the structure of the economy and GHG emissions within a metropolitan area and its host regional economy. Firstly, how direct emissions vary between sub-regions; secondly, to what extent GHG emissions are embodied in intraregional trade (i.e. inter sub-regional trade); thirdly, how produced and supported emissions per capita vary across sub-regions; and fourthly, what these results suggest for the choice of accounting method for local emissions targets and policies.

The next section reviews the relevant environmental, urban, and interregional input-output (IO) literature, and places the analysis in the context of previous work. Section 3 discusses the characteristics of the three sub-regions in our model. Section 4 outlines the database and model used in this study. Section 5 presents results and the final section concludes.

2 Input output, the urban economy, and greenhouse gas accounting

Input-Output (IO) and other economic accounting/modelling approaches have been widely used to analyse the interdependency between different spatial entities of the economy. Furthermore, these approaches have been used to analyse emissions attributable to various spatial levels. So far these two strands of work have seen a degree of cross-fertilisation, in particular interregional analysis of emissions. However, as of yet the structural detail afforded by urban IO models has not been extended to include GHG emissions.

Within metropolitan areas differences in population densities, economic activity, and emissions are often sharply evident between a core and a periphery. This is illustrated in our case by the data (Table 1) but also in a more abstract way in theoretical models (for an overview see McCann (2001)). As pointed out by the economic geography literature (for example (Krugman 1991)), economies of agglomeration create 'hubs' of activity in certain areas of a region or country. The location of these 'hubs' in turn influence the spatial distribution of GHG emissions[2], but these 'hubs' could shift in response to emissions abatement policies.

It has been pointed out in other contexts that the composition of the metropolitan area becomes particularly relevant when functional and administrative boundaries are not aligned (Hewings & Parr 2007, Hewings et al. 2001), as is often the case. For our study area, both the GLA and RST sub-regions are highly economically interdependent, but different administrative units control GLA and RST; indeed RST is comprised of a number of local authority areas. This raises additional complications in terms of policy coordination.

[2]For instance, increasing emissions in the area if the hub activity is emissions intensive, or reducing emissions if the creation of the hub results in existing emissions intensive activities relocating to other areas.

A particular strength of the IO approach is that it can capture the rich pattern of economic interdependence between sub-regions. In addition, it can capture interindustry linkages, and by extension the links between production sectors and households. Therefore, it is not surprising that a number of authors have applied interregional IO to model the detailed structure of the metropolitan economy. For a textbook exposition on interregional IO see Miller & Blair (2009, Ch. 3), while early examples include Isard (1951) and Leontief et al. (1953).

A number of authors have used interregional IO to focus on a particular region or locality within a national model to capture interdependencies between a local economy under analysis and its host region. For example Eskelinen (1983) used a multi-region IO model of Finland with two sub-regions, one the most economically advanced region around the capital Helsinki and the other, for contrast, the rural North Karelia. Similarly, Akita & Kataoka (2002) examine the Kyushu region in Japan and explore its interdependencies with the economically dominant Kanto region (Tokyo and surrounding areas) and the rest of Japan. Madden (1985) extends traditional IO to explicitly allow for commuting and shopping trips within a large regional economy, that of North Rhine-Westfalia in Germany. Jun (1999, 2004) focuses on applying IO to capture the richness of the metropolitan economy. He emphasises the relative importance of household consumption and extends a multizonal IO system to allow for spatial variation in the place of production, place of income (residence), and place of consumption.

Hewings et al. (2001) draw on the work of Miyazawa to examine the interdependencies between inner city localities and the suburbs within the Chicago metropolitan area. They find that the degree of interdependency depends on whether the focus is on production, employment, or income: "While the interindustry relationship generates circulation of economic activity and hence creates impacts outside the region of original stimulus, the size of these impacts is relatively small. The greatest source of this variation originates in the journey-to-work trips, that is, commuting" (p. 214). Furthermore, they find these spillovers to be asymmetric with significant income flows from inner city regions to the suburbs, reflecting commuter flows. This point is further picked up by Hewings & Parr (2007) who argue that the role of space has not received sufficient attention in economic analysis at the metropolitan level and that this neglect has sustained a perception of economic division between the central city and the suburbs. This has downplayed intra urban spillover effects and reinforced a view that development within a metropolitan area is effectively a zero sum game.

2.1 Extended IO and carbon accounting

Leontief (1970) extended the demand driven IO model to analyse environmental issues. This approach has subsequently been widely used in the carbon accounting literature, both for single region and inter-regional analyses. Munksgaard & Pedersen (2001) explore the attribution of air emissions under the territorial accounting principle (TAP) and the consumption accounting principle (CAP).

The TAP attributes all emissions to the territorial areas where the emissions are generated, while CAP attributes all emissions to the consumption that requires the generation of these emissions; irrespective of the spatial location of the emissions generation. Munksgaard & Pedersen (2001) demonstrate that in circumstances where there is a significant volume of trade between countries (or regions) TAP based emissions might prove problematic in practice. The reason being that how strict a region or country's emissions targets are can be sensitive to the emissions content of trade.

Munksgaard & Pedersen (2001) raise the case of Norway and Denmark in the

1990s, when in wet years, surplus quantities of hydropower generated in Norway were sold to Denmark. This had the effect of lowering Denmark's demand for power from traditional (dirty) power plants. This meant that Denmark's TAP targets, which were calculated relative to the emissions level in that year, were particularly tough and difficult to meet. This case was then used to illustrate that adopting a consumption accounting principle (CAP) instead would avoid this difficulty.

Subsequent papers then sought to examine the TAP and CAP totals for different countries, particularly in the context of the implications for local 'sustainability'. There is now a well-developed literature on the attribution of air emissions under both the TAP and CAP principles. Some examples here include: Druckman & Jackson (2009) for the UK, Turner et al. (2011) for Wales, a region of the UK, Peters & Hertwich (2006) who looked at the Norwegian case, Sánchez-Chóliz & Duarte (2004) who looked at the case of Spain, Mäenpää & Siikavirta (2007) for Finland, and Ipek Tunc et al. (2007) for Turkey.

There has been some scholarly debate on the attribution and accounting of emissions at the sub-national level, see for instance Turner et al. (2011), but at the sub-regional level applications are rare. One exception is Wu (2011) which looks at the carbon footprint of the Municipality of Haninge in Sweden.

There is also a substantial literature on interregional attribution and accounting analysis, for instance Lenzen et al. (2004) who examines CO_2 emissions in the context of interregional IO models. Wiedmann (2009) is a useful review paper on interregional emissions attribution and accounting literature, as Peters & Hertwich (2009) is for interregional (or multi-regional) industrial ecology attributions. An important application in the context of the analysis undertaken here is McGregor et al. (2008) who analyse the emissions embodied in trade between Scotland the rest of the UK.

3 Glasgow metropolitan area and the rest of Scotland

The city in our model is Glasgow, which is the largest city in Scotland, with a metropolitan area (comprising Glasgow (GLA) and the rest of Strathclyde (RST)) of approximately 2.13 million inhabitants. We separately identify in our model the Glasgow City Council Area (GLA), which is a single local authority and comprises the central city. Although GLA is a separate political unit and there is significant demand for economic policy analysis based solely on Glasgow[3], it is not a separate economic entity in functional terms. Rather, it is highly interdependent with other local authority areas in Scotland. Therefore, our second sub-region of analysis is Glasgow's wider city-region in the rest of Strathclyde (RST), which has strong links to Glasgow through commuting and shopping trips.

The RST is composed of several local authorities, but we amalgamate these into one sub-region to simplify the analysis[4]. The third sub-region we identify is a residual, the rest of Scotland (ROS). This is useful as the database can be constructed by disaggregating the relatively rich economic and environmental datasets available for Scotland, i.e. the official Scottish IO-tables and the environmental accounts. The Strathclyde sub-region is Scotland's largest pop-

[3]For example, Glasgow City Council and Scottish Enterprise have joined forces in the Glasgow Economic Commission, specifically charged with developing an economic strategy for the City: `http://www.glasgoweconomicfacts.com/Dept.aspx?dept_id=191`

[4]The boundaries of the Strathclyde sub-region as depicted in this study conform to those of the Strathclyde Regional Council (SRC). This includes the council areas of East Dunbartonshire, West Dunbartonshire, Helensburgh and Lomond, East, North and South Ayrshire mainland, Inverclyde, East Renfrewshire and Renfrewshire, North and South Lanarkshire. The SRC was one of nine regional councils created by the Local Government (Scotland) Act 1973 and came into operation in May 1975. It was responsible for various public services, including education, social work, police, fire services, water sewage and transport. Regional Councils were abolished in 1996 but many public services in the area are still provided by entities operating at the Strathclyde level, such as Strathclyde Police, Strathclyde Fire and Rescue Service, and the Strathclyde Partnership for Transport, which runs public transport in the region.

ulation and economic centre, containing 41.7% of its population and 41.1% of total employment. At its centre is the City of Glasgow, which is linked via an extensive suburban rail network to the rest of the Strathclyde sub-region. Figure 2 lays out the demarcation of the IO-regions in terms of NUTS 2 and NUTS 3 regions, while Figure 1 provides a map of the three sub-regions. Furthermore, key economic and social indicators for these areas are given in Table 1.

Within Strathclyde the main focus is on the Glasgow City Council jurisdiction, which spans an area of 175 km^2 and included 581 thousand inhabitants in 2006 (the year for which our database is constructed). Roughly 313 thousand full time equivalent jobs are found in Glasgow, which is approximately 17% of total employment in Scotland. This is a much larger share of Scotland-wide employment than Glasgow's population share would suggest. Indeed, as is illustrated in Table 2, four out of every ten jobs in the City are taken by in-commuters, primarily originating from other parts of the Strathclyde sub-region.

The rest of the Strathclyde sub-region (RST) has somewhat different economic characteristics than Glasgow (GLA). In terms of population it is approximately 3 times the size of Glasgow. However, there are only 1.4 times as many jobs in RST as there are in GLA. As is evident from Table 2, the lower job density in the RST sub-region is explained by significant out-commuting to seek employment in Glasgow (40% of all those working in Glasgow come from the rest of the Strathclyde sub-region). Furthermore, households in RST bring significant amounts of consumer spending to GLA (Hermannsson 2013). Therefore, it should be clear that there are strong links within the Strathclyde sub-region, between RST and GLA, through economic activity, transport, and governance.

The third sub-region, the Rest of Scotland (ROS), is determined as a residual that allows the interregional table to conform to the full Scottish IO table for control totals (Hermannsson 2013). This approach of identifying the two regions of main interest for analysis and treating the rest of the country as a residual is similar to that used by Akita & Kataoka (2002) for Japan and Eskelinen (1983) for the study of Finland.

4 Model and data

To conduct the CO_2 attribution analysis we apply an interregional emissions extended model. The details of such models have been widely discussed in previous literature. For example, Oosterhaven & Stelder (2007) provide an accessible introduction to interregional IO models and multipliers, while Wiedmann et al. (2007) offer a good exposition of the interregional emissions extended model. We build and extend on these standard models by incorporating features from metropolitan IO models, that is the interregional flow of wages (through commuting) and household consumption (through shopping). In the remainder of this section we explain these features of the model and detail how the underlying economic environmental database is constructed. A formal derivation of the 3-region emissions extended IO model is provided in Appendix.

4.1 The economic-environmental model and database

The outline of a standard IO table is presented in Figure 3. The IO-table has i intermediate sectors, q final demand sectors, and p primary (i.e. value added categories) sectors. The matrix notation and dimensions are as follows (small bold cases for vectors and capital bold cases for matrices):

$\mathbf{x}$ = (i x 1) vector of outputs

$\mathbf{Z}$ = (i x i) matrix-of intermediate demand

$\mathbf{Y}$ = (i x y) matrix-of final demand

$\mathbf{V}$ = (p x i) matrix of primary inputs

The aim of this section is to disaggregate the table above into 3 sub-regions as presented schematically in Figure 4. Again, the superscripts indicate the spatial origin and destination of the matrix elements, with G representing Glasgow, W the rest of the Strathclyde sub-region and S the rest of Scotland. The order follows the familiar row/column convention for matrix elements, for example the matrix $\mathbf{Z^{WG}}$ contains the elements for the intermediate demand rows of the rest of Strathclyde sub-region (W) and the intermediate expenditure column of Glasgow (G).

For final demand $\mathbf{Y}$ and primary inputs $\mathbf{V}$ the table is more complicated. Final demand is comprised of two parts, y_1 and y_2. The household consumption category of final demand (y_1) has a region of origin and a region of destination, and is represented by the interregional matrices $\mathbf{Y^{GG}, Y^{GW}, Y^{GS}, Y^{WG}, Y^{WW}, Y^{WS}, Y^{SG}, Y^{SW}, \text{and } Y^{SS}}$. The other categories of final demand (y_2), which includes government, export, capital, etc, final demands, are not assigned a spatial origin (from within the interregional IO-accounts), and are denoted as $\mathbf{Y^{G*}, Y^{W*}, Y^{S*}}$.

Details of the disaggregation process are provided in Hermannsson (2013). It should be noted that the table is constructed at a maximum level of disaggregation as allowed by the Scottish IO-table (126 sectors). At a later stage, sectors are aggregated to match environmental data and finally the table is aggregated to 12 sectors to aid in the presentation of results.

To estimate the flow of intermediate trade between the three sub-regions we employ employment based location quotients. Location quotients have frequently been found to underestimate interregional transactions; thereby overestimating local impacts see e.g. Harris & Liu (1998). However, a significant amount of efforts has been exerted to find methods that can counter this bias. Here we use the FLQ formula (Flegg & Webber 1997), which empirical testing has found is able to recreate, on average, the multipliers obtained from a survey based IO table (Tohmo 2004, Flegg and Tohmo 2011). Therefore, we are confident that in aggregate our interregional transactions matrix gives a reasonable approximation of the extent of intermediate transactions that occur across regional boundaries. A detailed discussion of the approach and sensitivity analysis of multipliers can be found in Hermannsson (2013).

For primary inputs, industrial sectors in each sub-region are assumed to have the same need for inputs as the aggregate sector in Scotland. These inputs are not assigned a spatial origin, with the exception of labour, where this is explicitly identified based on the commuting data presented in Table 2. For simplicity we assume a homogeneous sectoral commuting patterns, in that the same proportion of employees in each sector commute from each sub-region to the other, and furthermore that commuting employees take a pro-rata share of wages. This is a pragmatic assumption that was made to overcome a data gap. However, existing literature on commuters tells us that in general the extent of commuting is positively associated with factors such as income and education (Harsman & Quigley 1996). Therefore the estimates of interregional wage income flows should be seen as conservative.

Similarly, most final demand categories are based on employment shares with the exception of exports, which are determined as a residual, and household consumption, for which regional origin and destination is identified. This approach is consistent with most metropolitan models where it is recognised that household consumption is not necessarily incurred locally, but that people may travel for shopping. In principle this has been solved in metropolitan IO models by specifying an interregional shopping matrix that determines the spatial distribution of household outlays, e.g. (Hewings et al. 2001, Madden 1985). However, it is not clear what data are used and how they are constructed. We adopt a simple approach that determines net consumption flows across spatial boundaries by estimating separately the origin of demand (based on disposable household income) and the destination of demand (based on capacity of local sector to supply), with the difference determining the net-flow that has to be met outside the region (for details see (Hermannsson 2013, pp.18-21)). As this approach ignores potential cross-hauling in household consumption it should be seen as conservative. However, as Hermannsson (2013) finds, this is a significant improvement over assuming all consumption occurs locally.

4.2 Specification of emissions coefficients

In order to specify a vector of CO_2 emissions, we use CO_2 emissions data from the Scottish Government's Environmental Accounts published as part of the Scottish National Accounts Projects [5]. These accounts separately identify the CO_2 emissions of 93 industrial sectors. We aggregate both the 126 sector economic (IO) database, and the 93 sector environmental accounts, to 67 sectors for compatibility; then for convenience our results are presented at the 12 sector level as illustrated in Table 3.

The CO_2 emissions are reported on a Scotland-wide basis. In order to attribute emissions to the sector in each sub-region, we first calculate regional sector average emissions intensities, then we apply these to each sector's output (recalling that sectoral output is disaggregated by sub-region using employment shares) in each sub-region to calculate the emissions generated by each sector in each sub-region.

We therefore assume that sectoral output in each sub-region is equally emissions intensive, which for most sectors is a reasonable simplification. For sectors composed of many small units, such as say retailing, even if there is variation

[5] The environmental accounts, and the database used here entitled 'Greenhouse Gas Emissions by 93 Economic Sectors', are available at: `http://www.scotland.gov.uk/Topics/Statistics/Browse/Economy/SNAP/expstats/EnvironmentalAccounts`

in the emissions intensity of each retail unit, it seems reasonable to assume that the average CO_2 intensity of the regional sector provides an approximation for the actual emissions intensity of the sector.

In other cases this can be more problematic. In particular, where the sector is composed of a few heterogeneous plants applying the regional average may not be appropriate. The most acute example of this is electricity generation, where the bulk of the output is produced by a few plants with widely different emissions intensities, everything from hydro to coal. Furthermore, these plants may not be employment intensive, whereas the administrative offices are, and hence employment is likely to be a poor predictor of the spatial distribution of emissions.

To address this problem, we draw on data from the Scottish Pollutant Release Inventory, managed by the Scottish Environmental Protection Agency. The dataset contains the CO_2 emissions of all electricity generating plants that emit in excess of a reporting threshold[6]. We use this database to assign the emissions associated with each electricity generation plant to each of the three sub-regions, using the postcode of the plant to identify which sub-region it is located in. The remaining emissions of this sector[7] are attributed to the three sub-regions using employment shares, as employment is likely to be a good indicator of the scale of non-generation activities in each sub-region.

[6] For details see: `http://www.sepa.org.uk/air/process_industry_regulation/pollutant_release_inventory/reporting_thresholds.aspx`

[7] The emissions attributable to this sector in the Scottish Environmental Accounts are greater than those reported in the Scottish Pollutant Release Inventory. Since we are seeking to disaggregate the Environmental Accounts total, we split out the residual volume of emissions (i.e. the emissions for the electricity sector from the environmental accounts minus the sum of the electricity generation plant emissions from the Scottish Pollutant Release Inventory) between the three sub-regions based on sectoral employment in the three sub-regions.

5 Results

Given our focus in this paper on sub-regional emissions, we use the term 'CAP emissions' slightly differently to the existing literature. Here we think about CAP emissions as referring only to the emissions embodied in consumption from other parts of the same region. Typically in the CAP (commonly called a Carbon Footprint) case, an estimate is made of the emissions embodied in our consumption of goods produced outside of our region. Given our interest here is in the sub-regional level, in this analysis we ignore any external (outside the region) impacts, and carry out a consumption based attribution of the regional territorial emissions total. This retains consumption as the driver of the attribution of TAP emissions between sub-regions.

In this section we outline, firstly, the direct emissions generation for each of our sub-regions, before examining the emissions supported by consumption in each of our sub-regions. We then adjust these results to account for the different scales of the three sub-regions using data on the size of the resident population, and construct emissions measures in per capita terms.

5.1 Direct production emissions generation

We begin our discussion of these results by examining the direct generation of CO_2 emissions in each sector and sub-region- this does not require any IO attribution, but simply follows from the economic database and the environmental accounts. Table 4 documents the CO_2 emissions directly generated by each of our 12 economic sectors in each of our three sub-regions. This makes it clear that the biggest direct generator of emissions in Glasgow is 'Transport & Communications', in the rest of Strathclyde it is the 'Manufacturing' sector, and in the rest of Scotland- by quite some distance- the largest sector for the generation of CO_2 emissions is the 'Energy' sector.

These results are presented in aggregate form in Table 5, which also presents data on the direct generation of CO_2 emissions by households in each sub-region. While household consumption is considered to have the same emissions intensity (CO_2 per £m) in all sub-regions, household consumption differs between these sub-regions. As a result, while from Table 1 the rest of Scotland sub-region contains 58% of Scotland's population, from Table 5 they generate 59.4% of household direct emissions in Scotland.

Table 5 also shows that the Glasgow sub-region generates 8.31% of the direct production emissions in Glasgow, but from Table 1 contains 17% of the employment in Scotland. Similarly while the rest of Scotland sub-region contains (from Table 1) 59% of the jobs in Scotland, it is the sub-region where 77.47% of the direct production emissions in Scotland are generated. This is largely due to the fact that the majority of electricity generation (from Table 4 the largest sector in terms of the generation of CO_2 emissions in Scotland) takes place in the rest of Scotland sub-region.

5.2 Emissions supported by final demand

In order to capture the emissions interdependencies between each of the sub-regions, we have to look at the emissions that are supported by the demand of each of the sub-regions. We use the emissions attribution approach detailed earlier to assign the emissions generated by each economic sector in each sub-region, to each category of final demand. The results of this analysis are presented in Table 6.

The first row of Table 6 shows the emissions supported by the consumption of households based in the Glasgow sub-region, broken down by the sub-region in which those emissions are generated. This shows that Glasgow based households, through their consumption, support the generation of 413,108.73

tonnes of CO_2 in the Glasgow sub-region, 71,235.58 tonnes of CO_2 in the rest of Strathclyde sub-region, and 819,943.83 tonnes of CO_2 in the rest of Scotland sub-region. The subsequent rows for the rest of Strathclyde and the rest of Scotland sub-regions can be similarly interpreted.

In addition, Table 6 shows us that Glasgow based households support the generation of 12% of the production emissions generated in the Glasgow sub-region. This compares to 17% of the production emissions in the rest of Strathclyde being supported by the demands of households in the rest of Strathclyde, and 20% for the rest of Scotland sub-region.

Scotland is a small open regional economy that trades extensively with both the rest of the UK (RUK) and the rest of the world (ROW). As a result it is unsurprising that a large part of the emissions generation in all three of our sub-regions is supported by external demands; particularly important here are CO_2 emissions associated with exports to the RUK. We ignore these emissions in this analysis, because from a traditional CAP emissions perspective, these emissions would be attributed to the destination country for these goods.

5.3 Interregional emissions trade

Another way to explore the emissions interdependencies between sub-regions is to examine the household emissions trade balance between sub-regions, this is presented in Table 7. For ease of comparison, we provide the emissions supported by households in each of the three sub-regions, by sub-region where the emissions are generated (previously provided in Table 6), again at the top of Table 7. These results have already been interpreted in Section 5.2.

The emissions trade balances are shown at the bottom of Table 7. The first row of this part of the table (Household Emissions balance with GLA) shows that Glasgow runs a trade deficit in household emissions with the RST on the order of nearly 300,000 tonnes of CO_2[8]. That is, RST household consumption depends on GLA production activity (and hence emissions) more than GLA households depend upon RST production activity, in terms of CO_2 emissions, to meet their consumption needs.

While there isn't much heavy industry in GLA, and hence it might be said that there are 'few emissions involved in bean-counting', the sheer scale of economic activity in Glasgow means that there is a significant environmental impact for what, on the face of it, is not particularly emissions intensive activity. The dependence of RST households on the output of GLA sectors is what is driving this result.

The emissions trade balance between GLA and ROS is also worth commenting on. In this case GLA runs a significant trade deficit in emissions with the ROS. This is being driven by consumption of electricity, largely produced in ROS, by GLA households. However caution has to be exercised in relation to the ROS sub-region as it is modelled as a residual sub-region and therefore includes a mixture of major cities and rural areas.

5.4 Comparing GHG emissions per capita

In the previous sub-sections of this paper we compared the emissions generation in each sub-region to the proportion of Scottish employment in each sub-region. We also compared the emissions supported by the household demands of each sub-region and the resident population of each sub-region. We saw, for instance, that with 17% of total Scottish employment, Glasgow generated only 8.31% of Scottish emissions.

In order to better compare how each sub-region's emissions that are generated directly, but also supported through consumption, compare relative to one

[8]The calculation here being: Emissions embodied in GLAs exports to RST households (370,348.12 T CO_2) minus emissions embodied in RSTs exports to GLA households (71,235.58 T CO_2).

another we have to control for differences in the scale of each sub-region using per capita measures; these are contained within Table 8. In order to understand the emissions interdependencies between the three sub-regions in our analysis, while controlling for differences in the population size, we calculate the following two measures:

- The emissions generated in each sub-region to satisfy total household final demand in Scotland (for instance, the emissions generated in the Glasgow sub-region to meet Scottish households' final demand), per capita based on the sub-region of generation. These are in the first row of Table 8.
- The emissions supported in Scotland by the final demands of households in each sub-region (e.g. the total emissions in Scotland supported by the final demands of households in the GLA sub-region), per capita based on the sub-region where the household demand originates. These are in the second row of Table 8.

The first row of Table 8 shows that there is clearly heterogeneity in terms of the impact of Scottish household demand on emissions generation in each of the sub-regions. Scottish households' final demand results in the generation of emissions per capita in ROS of 5.72 compared to 4.41 in GLA, and 3.43 in RST. This is, we believe, a consequence of the fact that most electricity generation activity, and in particular the emissions intensive electricity generation activity, is not located in either the GLA or RST sub-region.

Electricity is an important purchase by households, and is also very emissions intensive. Table 8 illustrates an important interdependence between the sub-regions; that household demands in each sub-region will rely upon specific production activities (such as electricity generation) that might be located in other sub-regions. In this case the emissions generation per capita in support of household final demand is far greater in ROS than in GLA.

When we look instead at the emissions that each sub-region's households support in Scotland as a whole, per capita, we see much greater homogeneity, which is not surprising. Household's demand patterns and consumption bundles are not anticipated to vary greatly between sub-regions, and therefore the emissions generated in Scotland as a whole, and embodied in the household demands of each sub-region, are not expected to be much different.

However, the results in Table 8 suggest that there is significant heterogeneity in terms of the emissions generated in each sub-region to support Scottish households' final demands. This suggests that there are difficulties in using local territorial based (TAP) emissions targets or measures given the extent to which the emissions generated in any given sub-region are being driven by the consumption demand of other sub-regions.

The adoption, for instance, of local level TAP emissions targets may result in greater costs being imposed in some sub-regions than may seem reasonable on the basis of their consumption patterns. In essence, we argue that when implementing sub-regional emission reduction effort, there can be a spatial mismatch- as demonstrated in our case (Table 8) by the differences in emissions per capita in each of our three sub-regions in support of total Scottish household demands (shown in the first row).

In addition, given that sub-regional CO_2 emission reduction efforts are likely to be funded directly by local authorities (and hence at least in part by taxes paid by local citizens), it would seem potentially unfair to focus on the emissions that are directly generated within a local authority area, which could potentially penalise areas of high economic activity but benefit suburban and wider metropolitan areas, instead of the emissions supported by local consumption activities; a measure that is relatively invariant to the spatial location of productive activities.

6 Conclusions

This paper has sought to illustrate the difficulties involved in the attribution of CO_2 emissions at the sub-regional level. The model presented here enabled us to attribute CO_2 emissions at the sub-regional level and identify the emissions generated in production and supported by consumption in each sub-region in Scotland. Doing so allowed us to identify the extent of emissions interdependence between our three sub-regions. This provided a good means of exploring how functional specialisation between our three sub-regions can drive inter-regional trade and the associated embedded emissions.

In the Scottish case it is clear that electricity generation in the ROS is an important determinant of total emissions generation in Scotland, however perhaps more interesting for us is the interdependence between Glasgow and the rest of Strathclyde; the city and the wider metropolitan area. The city and the wider metropolitan area play different roles and fulfill different functions in the economy, something recognised previously in the economic and urban economic literature, but until now not recognised in the emissions attribution and accounting literature.

The results of our attribution analysis show that territorially based emissions are skewed by economic structure and composition. This needs to be considered when local level emissions policies are formulated. For example, local carbon targets based on territorial emissions generation would disproportionately impact areas where economic activity is concentrated to the benefit of other areas, such as the wider metropolitan/suburban area.

In our case, this would disadvantage Glasgow to the benefit of the rest of Strathclyde area. This approach would lead to a spatially unbalanced burden of adjustment towards the targeted level of emissions, i.e. more of the abatement would fall on areas of higher job densities (central cities) and less on areas of low job densities (wider city-region). A consumption based accounting approach, in contrast, would lead to a more equal attribution of CO_2 emissions between sub-regions; since consumption behaviour between sub-regions is more homogeneous than production activities between sub-regions.

Future work will further develop the database to allow us to examine issues surrounding household heterogeneity by disaggregating households by income. Some of the most interesting research questions will require us to look at the *distribution* of impacts. In the case of our analysis here, an interesting issue to look at would be *who* is supporting what volume of emissions in which sub-region. Is it the case, for example, that a city advancing an emissions abatement strategy to reduce their territorial emissions, and paying to do so, is in essence taxing poorer households in cities to abate the emissions generated to meet the consumption needs of richer households in the suburbs? Such redistributive impacts could have severe implications for regional or national emissions abatement spending.

A 3-region interregional emissions augmented IO-model

Our starting point is the standard Leontief model (see Leontief (1970), Miller & Blair (2009)):

$$(I - A)^{-1}Y = X \tag{1}$$

The matrix $(I - A)^{-1}$ is the Leontief inverse. This is used to calculate the $N \times 1$ vector of gross outputs, X, (with elements x_i, where $i = 1, , N,$) from the vector of final demands, Y, the $N \times 1$ vector of final demands with elements y_i. Each element of the Leontief inverse, α_{ij}, measures the direct, indirect (and where appropriate induced) impact on sector i of a unit increase in the final demand for sector j. These are effectively sector-to-sector multipliers. The value of m_j, the output multiplier for sector j, is found as the sum of the elements of the j^{th} column of the Leontief inverse.

This is a sector-to-economy multiplier, that relates final demand in sector j to economy-wide output.

$$m_j = \sum_i \alpha_{ij} \tag{2}$$

This basic approach can easily be augmented to link the exogenous elements for demand not only to the value of output but also to the emissions generated in the production of that output (see Turner et al. (2007), Miller & Blair (2009, ch. 10)).

Total greenhouse gas generation in production is determined as:

$$f^x = \Omega x \tag{3}$$

where f^x is a $K \times 1$ vector, with elements f_x^k, where $k = 1, \ldots, K$, representing the total greenhouse gases k generated by all production activities in the economy. Ω is a $K \times N$ matrix where element $\omega_{k,i}$ is the average generation of emissions k per unit of gross output in sector i.

Then the standard Leontief model (Leontief, 1970; Miller & Blair, 2009) can be employed so that it is extended to $f^y = \Omega(I - A)^{-1}Y$ where f^y is a $K \times 1$ vector, with element f_y^k, being the total generation of emissions k directly or indirectly required to satisfy total final demand, y, in the economy. In our case final demanders (households) also directly generate emissions (for instance by combusting fuels and driving cars) and hence Eq. (3) is extended for final demand as $f^y = \Omega(I - A)^{-1}Y + \Omega^y y$ where we distinguish the $K \times N$ matrix of emission coefficients for the N production sectors, now relabeled Ω^x,from a

$K \times Z$ matrix, Ω^y, where each $K \times 1$ column within has elements $\omega_{k,z}$ as the average direct use of resource k per unit of expenditure by final demand group z.

The single region model is useful for demonstrating the principle of emissions extended IO. However, for our application we want to develop a 3-region emissions extended IO-model to fit our database. This is the emissions extended version of the 3-region model set out in (Hermannsson 2013). For examples of interregional environmentally extended IO-models, see Wiedmann et al. (2007) and Miller & Blair (2009, ch. 10).

In Eq.(1) we identified the key equation determining the $N \times 1$ vector of output X in the single region IO framework. The superscripts indicate the spatial origin and destination of the matrix elements, with G representing Glasgow, W the rest of the Strathclyde region and S the rest of Scotland. We take this as representing a single region in a 3-region world and separate the final demand (Y) into local final demand for locally produced commodities and export demand from other regions for commodities:

$$\begin{bmatrix} I - A^{GG} - A^{GW} - A^{GS} \\ -A^{WG} I - A^{WW} - A^{WS} \\ -A^{SG} I - A^{SW} I - A^{SS} \end{bmatrix}^{-1} \begin{bmatrix} y^{GG} y^{GW} y^{GS} \\ y^{WG} y^{WW} y^{WS} \\ y^{SG} y^{SW} y^{SS} \end{bmatrix} = \begin{bmatrix} x^{GG} x^{GW} x^{GS} \\ x^{WG} x^{WW} x^{WS} \\ x^{SG} x^{SW} x^{SS} \end{bmatrix} \quad (4)$$

As in the single-region case the columns in the interregional Leontief inverse can be summed to obtain the convenient multipliers for individual sectors. Furthermore, in this case, the inverse can be partitioned so as to obtain not only a multiplier pertaining to the Scotland-wide impact of a particular sector, but to decompose the multiplier effect by the region of impact.

$$\left\{ \begin{bmatrix} I & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & I \end{bmatrix} - \begin{bmatrix} A^{GG} A^{GW} A^{GS} \\ A^{WG} A^{WW} A^{WS} \\ A^{SG} A^{SW} A^{SS} \end{bmatrix} \right\}^{-1} = \begin{bmatrix} \alpha^{GG} \alpha^{GW} \alpha^{GS} \\ \alpha^{WG} \alpha^{WW} \alpha^{WS} \\ \alpha^{SG} \alpha^{SW} \alpha^{SS} \end{bmatrix} \tag{5}$$

The Leontief inverse is partitioned into sub-matrices containing the elements α_{ij}^{RS}, the inter-industry multiplier. As before these matrix elements describe the impact of a change in the final demand for sector j upon sector i, but in the interregional variant sector j is located in region S and sector i in region R. If region R is the same as S, such as in the matrices on the diagonal α^{GG}, α^{GG} and α^{SS}, we have an intra-regional effect, where R and S are not the same the multipliers describe interregional effects. For example the sector by sector multipliers contained in the sub-matrix α^{GS} describe the impact of sector j in the rest of Scotland upon sector i in Glasgow.

For this application we are interested in the emissions generated by the production of output in each of the 3 regions. Just as we extended the single region framework to include emissions, we can introduce a $(K \times 3N)$ matrix of coefficients Ω^x showing the emissions intensity of output in each production sector and a $(K \times 3N)$ matrix of coefficients Ω^y showing the direct emissions intensity per unit of expenditure by final demand group z.

$$\begin{bmatrix} f^{GG} f^{GW} f^{GS} \\ f^{WG} f^{WW} f^{WS} \\ f^{SG} f^{SW} f^{SS} \end{bmatrix} = \begin{bmatrix} \Omega_x \end{bmatrix} \begin{bmatrix} \alpha^{GG} \alpha^{GW} \alpha^{GS} \\ \alpha^{WG} \alpha^{WW} \alpha^{WS} \\ \alpha^{SG} \alpha^{SW} \alpha^{SS} \end{bmatrix} + \begin{bmatrix} \Omega_y \end{bmatrix} \begin{bmatrix} y^{GG} y^{GW} y^{GS} \\ y^{WG} y^{WW} y^{WS} \\ y^{SG} y^{SW} y^{SS} \end{bmatrix} \tag{6}$$

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Table 1: Key social and economic indicators for each IO-region in 2006.

		GLA	RST	ROS	SCO
Population		580,690	1,555,374	2,980,836	5,116,900
	% of total	11%	30%	58%	100%
Employment	FTEs	313,535	448,296	1,089,529	1,851,360
	% of total	17%	24%	59%	100%
Gross Domestic Household Income Per Head		11,968	12,975	13,319	13,071
	% of average	92%	99%	102%	100%

Table 2: Origins and destinations of people who travel between Scottish addresses for work/study (headcount/column %). Own calculations, based on Fleming (2006, Table 16A, pp. 64-65).

		Place of work							
		GLA		RST		ROS		SCO	
Residence	GLA	246,938	59%	46,677	6%	4,743	0%	298,360	11%
	RST	167,322	40%	727,112	93%	16,258	1%	910,694	32%
	ROS	5,961	1%	6,335	1%	1,613,211	99%	1,625,507	57%
		420,221	100%	780,125	100%	1,634,212	100%	2,834,560	100%

Table 3: Sectoral aggregation scheme

Env Acc Code	123 sector IO code	12 sector	12 Sector name
1	1	1	Agriculture, forestry & fishing
2	2	1	
3	3	1	
4	4	2	Mining
5	5	2	
6&7	6&7	2	
8	8-19	3	Manufacturing
9	20	3	
10	21-27	3	
11	28	3	
12	29-30	3	
13	31	3	
14-15	32-33	3	
16-18	35	3	
19	36	3	
20-21	37 & 38	3	
22-24	39 - 41	3	
25	42	3	
26	43	3	
27	44	3	
28-29	45 & 46	3	
30	47	3	
31	48	3	
32	49	3	
33	50	3	
34-35	51 & 52	3	
36	53	3	
37-40	54 - 56	3	
41	57-61	3	
42	62-68	3	
43	69	3	
44	70-72	3	
45	73-75	3	
46	76	3	
47	77	3	
48	78-80	3	
49-50	81-84	3	
51-55	85	4	Energy
56	86	5	Other utilities
57	87	5	
58	88	6	Construction
59	89	7	Distribution & catering
60	90	7	
61	91	7	
62	92	7	
63	93	8	Transport & communication
64-68	94	8	
69	95	8	
70	96	8	
71	97	8	
72	98-99	8	
73	100	9	Finance & business
74	101	9	
75	102	9	
76	103-105	9	
77	106	9	
78	107	9	
79	108	9	
80	109-114	9	
81-82	115	10	Public admin, etc.
83	116	11	Education, health & social work
84	117-118	11	
85-87	119	12	Other services
88	120	12	
89	121	12	
90	122	12	
91	123	12	

Table 4: Directly generated CO_2 emissions by sector (Tonnes)

Sectors			Total emissions
GLA	1	Agriculture, forestry & fishing	47,035.03
	2	Mining	28,213.29
	3	Manufacturing	658,400.46
	4	Energy	830,536.81
	5	Other utilities	88,493.92
	6	Construction	142,115.77
	7	Distribution & catering	210,132.04
	8	Transport & communication	1,047,914.48
	9	Finance & business	133,490.37
	10	Public administration	170,179.60
	11	Educ., health & social work	108,141.78
	12	Other services	81,136.02
RST	13	Agriculture, forestry & fishing	249,022.00
	14	Mining	148,046.67
	15	Manufacturing	2,070,813.29
	16	Energy	587,119.10
	17	Other utilities	35,398.22
	18	Construction	320,827.34
	19	Distribution & catering	341,478.56
	20	Transport & communication	1,741,004.29
	21	Finance & business	91,848.34
	22	Public administration	220,258.37
	23	Educ., health & social work	146,626.45
	24	Other services	117,452.38
ROS	25	Agriculture, forestry & fishing	685,731.84
	26	Mining	2,345,076.36
	27	Manufacturing	4,931,068.10
	28	Energy	18,521,774.27
	29	Other utilities	533,987.91
	30	Construction	662,556.05
	31	Distribution & catering	841,723.43
	32	Transport & communication	3,080,099.99
	33	Finance & business	322,321.14
	34	Public administration	486,352.55
	35	Educ., health & social work	361,601.23
	36	Other services	287,829.13
		Total	42,675,806.59

Table 5: CO_2 Emissions (Tonnes) by sub-region of generation

	Where the emissions are generated							
	GLA	%	**RST**	%	**ROS**	%	**Total**	%
Direct production emissions	3,545,789.57	8.31%	6,069,895.01	14.22%	33,060,122.01	77.47%	42,675,806.59	100%
Direct household consumption emissions	1,278,047.50	10.39%	3,710,924.97	30.17%	7,310,045.10	59.44%	12,299,017.58	100%
Total emissions in each sub-region	4,823,837.07	8.77%	9,780,819.98	17.79%	40,370,167.11	73.43%	54,974,824.17	100%

Table 6: CO_2 emissions (Tonnes) from production as supported by Final Demand, by sub-region of generation

	Where the emissions are generated						
	Glasgow	% of total emissions generated	**RST**	% of total emissions generated	**ROS**	% of total emissions generated	**Total**
Households GLA	413,108.73	12%	71,235.58	1%	819,943.83	2%	1,304,288.13
Households RST	370,348.12	10%	1,037,555.93	17%	2,388,489.43	7%	3,796,393.48
Households ROS	497,236.02	14%	518,981.84	9%	6,538,322.07	20%	7,554,539.93
NPISHs[a]	37,933.04	1%	55,510.78	1%	173,285.05	1%	266,728.87
Non-Resident Household Expenditure[b]	62,047.53	2%	91,463.21	2%	262,291.27	1%	415,802.00
Central Government	350,696.59	10%	465,335.69	8%	1,317,277.92	4%	2,133,310.20
Local Government	185,833.07	5%	259,572.02	4%	736,408.19	2%	1,181,813.28
Capital[c]	260,506.51	7%	603,624.03	10%	1,486,111.08	4%	2,350,241.63
Rest of UK Exports	981,510.90	28%	1,890,046.58	31%	14,658,158.50	44%	17,529,715.98
Rest of World Exports	386,569.07	11%	1,076,569.34	18%	4,679,834.67	14%	6,142,973.09
Total emissions in each sub-region	3,545,789.57	100%	6,069,895.01	100%	33,060,122.01	100%	42,675,806.59

[a]Non-profit institutions serving households.
[b]This can be thought of as tourist spending, or more generally expenditure by non-residents.
[c]Gross fixed capital formation, Valuables, and Inventory Changes

Table 7: CO_2 emissions (Tonnes) attributed to spatially disaggregated households, by sub-region where the emissions are generated.

	Where the emissions are generated[a]			
	Glasgow	**RST**	**ROS**	**Emissions Total**
Households GLA	413,108.73	71,235.58	819,943.83	1,304,288.13
Households RST	370,348.12	1,037,555.93	2,388,489.43	3,796,393.48
Households ROS	497,236.02	518,981.84	6,538,322.07	7,554,539.93
Total emissions in each sub-region	1,280,692.87	1,627,773.35	9,746,755.33	12,655,221.55
Household Emissions balance with GLA	-	-299,112.55	322,707.81	
Household Emissions balance with RST	299,112.55	-	1,869,507.58	
Household Emissions balance with ROS	-322,707.81	-1,869,507.58	-	

[a] We have not included direct household emissions in this table, but these are shown in Table 5. These emissions are excluded from this table as they do not affect the trade in emissions.

Table 8: CO_2 emissions per capita (Tonnes)

	GLA	RST	ROS
Emissions generated in each sub-region to satisfy total Scottish Household demand, per capita	4.41	3.43	5.72
Emissions supported in Scotland by the Household demand of each sub-region, per capita	4.45	4.83	4.99

Figure 1: 3 Sub-Region Map of Scotland

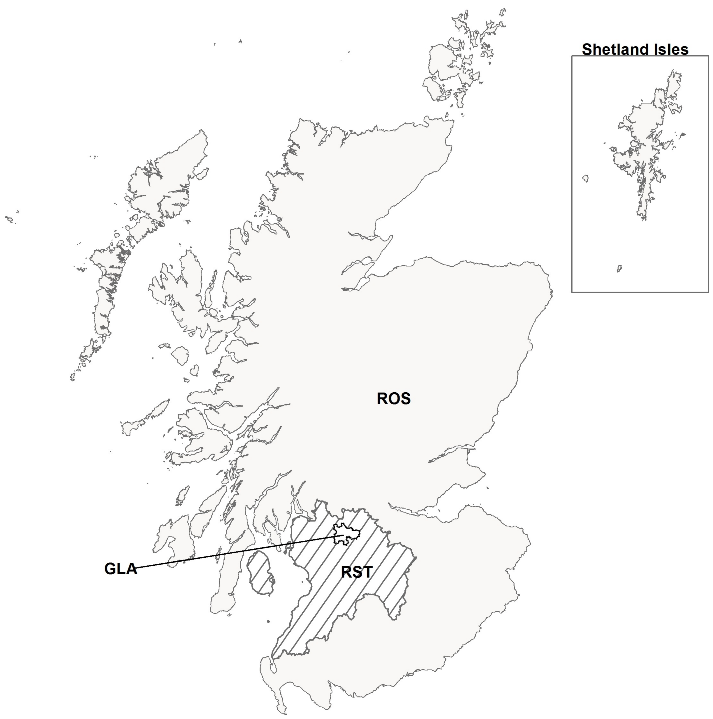

Figure 2: Demarcation of spatial zones in the GLA-RST-ROS IO-tables.

IO region		NUTS 2 Region	NUTS 3 Regions
Scotland (SCO)	GLA	South Western Scotland	Glasgow
	RST		East Dunbartonshire, West Dunbartonshire, and Helensburgh and Lomond; East and North Ayrshire mainland; Inverclyde, East Renfrewshire, and Renfrewshire; North Lanarkshire; South Ayrshire; South Lanarkshire
	ROS		Dumfries and Galloway
		Eastern Scotland	Angus and Dundee; Clackmannanshire and Fife; East Lothian and Midlothian; Scottish Borders; Edinburgh; Falkirk; Perth and Kinross, and Stirling; West Lothian
		North Eastern Scotland	Aberdeen and Aberdeenshire
		Highlands and Islands	Caithness and Sutherland, and Ross and Cromarty; Inverness, Nairn, Moray, and Badenoch and Strathspey; Lochaber, Skye and Lochalsh, Arran and Cumbrae, and Argyll and Bute; Eilean Siar (Western Isles); Orkney Islands; Shetland Islands

Figure 3: Single region IO-table for Scotland

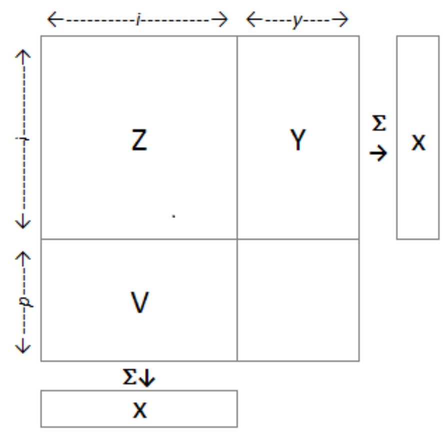

Figure 4: Interregional input-output table for three sub-regions (r = 3)