Spatial Specificity of Unit Process Data in Life Cycle Inventory Databases

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Abstract

The goal of Life Cycle Assessments (LCA) is to estimate the environmental impact of a product or service by analysing the outputs to the environment of each step in the product's life cycle. To do this, unit process data is necessary which represent individual self contained steps in this life cycle. In this study I analyse the spatial specificity, an important aspect of data quality, of unit processes across multiple Life Cycle Inventory (LCI) databases. Unit processes are classified into thematic categories and the regionalisation of unit processes per category is studied using qualitative and quantitative approaches. A comparison of the databases is carried out resulting in the conclusion that while there are certain unit process classes with systematically high or low regionalisation a lot of the spatial specificity of the data is highly reliant on data sources.

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1. Introduction

1.1 Life Cycle Assessment and Life Cycle Inventories

In the face of human induced climate change Life Cycle Assessment is a tool which has become important for businesses, individuals and policymakers. It allows the assessment of the environmental impacts of a product by analysing its entire life cycle. A term often used is "cradle-to-grave" which means that all the steps from the acquisition of the most basic resources over manufacturing, transport, use and finally to disposal and recycling are considered. The idea is thus to cover the entire life cycle of a product. Products can be any kind of goods or services. A full LCA can then be used to identify the most environmentally problematic step in a product's life cycle and to focus efforts in improving that phase which would ultimately lead to a more environmentally friendly product (Hellweg and Milà i Canals, 2014).

There are two types of LCA methods. One, the attributional LCA, puts its focus on the physical flows to and from a life cycle which are environmentally relevant. The other is the consequential LCA which concerns itself with the effect of decisions made which change these flows. Attributional LCAs are the more broadly applied method but there is debate on which one is superior for decision making (Finnveden et al., 2009).

LCAs can be divided into four phases: Goal and Scope Definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. The existence of appropriate LCI databases is a requirement for an LCA and their creation is the most time consuming part. Therefore there exists the need for LCI databases that can be used for multiple purposes, so that not every LCA must be preceded by an expensive gathering of data for an LCI. LCIs have been created by business associations from different branches but there has also been an effort to create national and international LCI databases which often contain data sourced from the individual business LCIs. These publicly available databases often apply a unit process approach to data gathering. This means that there is a dataset for each production step with a complete set of inputs and outputs per step. These unit processes can then be combined to receive a full LCA (Finnveden et al., 2009).

1.2 Focus and Procedure of this Study

In this paper I will focus on the second step (LCI) of an LCA or more accurately on LCI databases which contain the unit processes that are essential for LCA. The object of interest is the spatial specificity of these unit processes. Spatial specificity is a quality measure for unit processes (Rousseaux et al., 2001). It is defined by the area over which the unit process data is averaged. This influences the geographic representativeness of a dataset. Take for example measurements of inputs and outputs to a unit process like electricity generation from coal at a specific power plant. This unit process is very spatially specific as it represents site specific data for that process. The geographic representativeness is low as the proc-

ess represents the conditions in a very small area, the power plant itself. Regarding special specificity I seek to establish if there are certain types of unit processes which generally show a different regionalisation to others and if regionalisation is usually consistent within the same database.

This study of spatial specificity in LCI databases will start with an overview of the geographic factors (section 2) which make spatial specificity important and show why a unit process specific for one region might not represent the situation in another region accurately. This is followed by a presentation of multiple LCI databases (section 3) complete with a table which shows the averaged regions for each class of unit processes. For classification, I use the International Standard Industrial Classification of All Economic Activities (ISIC), Rev. 4. (Department of Economic and Social Affairs, 2008) as its classes provide a good differentiation between types of unit processes and it is a classification supported by multiple LCI databases. In the same section the unique aspects of each database are listed. In the next section (4) follows the comparison between databases including the discussion of similarities and differences regarding high or low spatial specificity across all databases. A conclusion (section 5) summarizes the main observations which were made in the comparison.

2. Geographic Factors

It might not be immediately apparent how geography can influence a unit process and why locally measured inputs and outputs of unit processes might not be universally representative. A very general way of describing the problem of spatial representativity is Tobler's so-called first law of Geography: "Everything is related to everything else, but near things are more related than distant things." (Tobler, 1970). While this is not true in every case it does describe circumstances on a certain scale, which might vary between continents and countries. In the following section I will list factors that can cause disparities between the same processes measured at different locations and thus subject them to Tobler's law. I will also try and assess the consequences of these differences. In naming the relevant processes I will be using the ISIC classification method .

2.1 Climate

Climate is defined as the sum of several meteorological variables such as humidity, precipitation, air pressure, wind and temperature at a certain location over a long time-period. It is influenced by insolation, water bodies, terrain, altitude etc. Daily averaged Insolation varies over the course of the year, creating unique climatic conditions at different latitudes at any given time. Terrain affects climatic conditions by causing precipitation and loss of humidity from air packages passing over them and influencing the wind regime. Warm water carried away from the equator by oceanic currents create regions with atypically high temperatures for their latitudes (Gebhardt et al., 2011). All these processes play together

in creating a diverse climatic pattern which means that certain processes have varying surrounding conditions if performed at different locations.

The ISIC division which is by far the most impacted by climate is division 01: "Crop and animal production, hunting and related service activities" with mainly crop production processes taking the brunt of climatic diversity. Strong regional contrasts in precipitation cause some regions to be more arid than others. This is then reflected in the higher input of water needed in arid regions to yield the same amount of crops as in more humid ones, sometimes needing complex irrigation systems to distribute the water which requires further energy inputs and environmentally problematic outputs. Temperatures could also result in differences in yield and in some cases crops could not normally be grown at the local temperatures, especially those belonging to the ISIC classes 0122 and 0123 (tropical and subtropical fruits and citrus fruits). This could cause the need for either additional fertilizer and/or heating in greenhouses, making the production in colder regions more environmentally costly.

2.2 Topography

Topography defines the shape of the earth's surface. It includes features such as mountains, valleys, hills and various other geomorphological features. As mentioned above, topography can have a significant effect on climate, sometimes even resulting in deserts (Gebhardt et al., 2011). Here I want to focus on additional effects that topography can have on unit process data.

To induce movement of mass up a steep incline requires more energy and thus more fuel than downwards where gravity is a driving force instead of a resisting one. Transportation of goods and people in a hilly region will require more electricity or fuel than in the flatland. This affects any transportation processes by land (ISIC Groups 491 and 492).

2.3 Soil

Unless soil is brought in from elsewhere it can be described as a function of the two described factors climate and topography in addition to organisms, parent material and time. The result of this function is spatially diverse on small (e.g. a valley slope vs. the valley bottom) but also on large scales. In deserts there is hardly any soil formation due to the lack of precipitation and organisms. In very humid and vegetated environments like rainforests there is more soil but the quality is poor due to nutrient leaching through heavy precipitation. The parent material can be assessed using geological maps. Here again there is a high spatial diversity due to geological processes (Stahr et al., 2012).

Soil quality is the other key factor for crop production next to climate and influences processes of ISIC division 01. The soil's natural nutrient content is important for the amount and the kinds of fertilizer used to support crop production. The fertilizers to apply are chosen based on soil test results. These fertilizers can have potentially detrimental effects on the environment by contaminating runoff with nitrate

which can lead to the eutrophication of lakes. The input as well as the output of chemicals from fertilizers is dependent on regionally diverse soil quality with more input needed in poor soils and more output created when not adjusting the dosage adequately (Fu et al., 2010).

2.4 Power Generation

Local means of generating electricity are dependent on the resources available as cost efficiency is important. The type of electrical power generation from fossil fuels used in a certain region is linked to local geology which includes coal, oil and gas deposits as well as the possibility for geothermal systems based on the geothermal gradient. The siting of fossil fuel power plants is often a tradeoff between resource and energy transportation. Power plants in the proximity of needed resources must transport the generated energy to the consumer which results in energy loss whereas power plants located in proximity of the consumers must transport a considerable amount of resources to the site (Calzonetti and Eckert, 1981). There are also fossil fuel power plants where the resources aren't locally sourced and brought in from distant mines but their location is linked with a historic mining industry (e.g. coal power plants in England). Climate decides the feasibility of wind and solar power generation by the yearly averaged wind-speed and insolation. Geomorphology dictates the locations of watercourses, their flow velocity and if they can be diverted or dammed to create an artificial lake in a valley. River power stations and dam power plants can only be built where the topography allows it.

Of course not all power plants are directly dependant on these factors, a prime example being nuclear power plants which are typically independent from Uranium mine locations. However it is possible that the choice of nuclear power was made due to the lack of other alternatives like water power because of suboptimal geographical factors.

ISIC class 3510 contains electric power generation, transmission and distribution all in one, and it is therefore processes of this class that are influenced by the locations of power plants and to a further extent the geographical factors mentioned. Averaged electricity mixes over large regions lose details regarding power plant distribution while more local electricity mix data better represents the specific methods used to generate the electricity. As emissions from different types of electric power generation vary greatly, a use of averaged mixes can cause deviations from the true environmental impact of an end-product (Hellweg and Milà i Canals, 2014).

3. LCI Database Spatial Analysis

In this section I will present the eight LCI databases which I analysed over the course of this study and include a table of my results per database. The LCI Databases to analyse were provided by Jürgen Reinhard and additional Databases were chosen from a list compiled by Bjørn et al. (2013) as well as from data publicly available from the openLCA nexus (OpenLCA, Accessed: 17.08.2014).

The spatial specifity of unit process data was analyzed for the following databases (data sources specified):

- NREL U.S. LCI Database Project (NREL, Accessed: 17.08.2014)
- ELCD (ELCD, Accessed: 17.08.2014)
- ProBas (ProBas, Accessed: 17.08.2014)
- Netzwerk Lebenszyklusdaten (Netzwerk Lebenszyklusdaten, Accessed: 17.08.2014)
- AusLCI (AusLCI, Accessed: 17.08.2014)
- USDA LCA Digital Commons (USDA, Accessed: 17.08.2014)
- NEEDS LCI Database (NEEDS, Accessed: 17.08.2014)
- ecoinvent (ecoinvent, Accessed: 17.08.2014)

I decided on a qualitative approach towards the analysis of all the databases except ecoinvent, which entailed a manual assessment of individual processes in the database. This, while time consuming, was necessary as many of the databases were not available in the same format and the same classification. For each database the unit processes were aggregated into classes using the ISIC classification and the tables were sorted according to these. A column "Geography" was added to each resulting table, detailing the geographical regions. For each ISIC class I detailed the geographical regions over which processes that adhere to that class are averaged. This would allow me to detail the levels of spatial specificity found in each class which will be important for comparison between databases in section 4.

Each database is introduced, with the origin and purpose of the database specified. If a database shows unique spatial specifities these are elaborated upon and in some cases the choice is commented.

As ecoinvent provides one of the most comprehensive datasets, including an overview file in xls format, I wrote a program which returns some quantitative information on the spatial specificity of the unit processes to add to the qualitative analysis of the other databases.

3.1 NREL

The National Renewable Energy Laboratory (NREL) concerns itself with energy innovation and is the main research and development institute for finding sustainable energy solutions in the U.S. It also hosts the U.S. LCI Database Project. The purpose of the Project is to help develop and provide the basis for any LCAs and LCA-based decisions of the public, private or non-profit sector. The goal is therefore to create a large data resource base which includes as many LCIs as could be helpful for such causes but not to include full product LCIs as these would be generated as a next step, by manufacturers, researchers, policy analysts etc. This assumes knowledge of the user and the database contents are therefore not intended for use by the general public. The database was created to be suitable for attributional but not consequential LCAs (U.S. Database Project User's Guide, Accessed: 17.08.2014).

The creators are confident that LCA is a growing trend and will be used by most companies in the future when assessing their environmental impact. The database must be standardized and therefore compliant with ISO 14041 (now 14040) (U.S. Database Project User's Guide, Accessed: 17.08.2014).

The processes in the database are not classified according to ISIC or CPA categories. The classification is given in Category and SubCategory although these do not seem to be entirely consistent throughout the database, possibly on the grounds that the data is taken from different databases. For example there is a category named Glass and Glass Product Manufacturing as well as another category named Nonmetallic Mineral Product Manufacturing from which glass is exempt. The following table notes the geographies used in each NREL category (for each geography noted there is at least one unit process in the category which is aggregated on that geographical level) and also includes the ISIC class the category equates to. Where the NREL category is too general merely the ISIC group is given.

Abbreviated geographical regions used: GLO: Global, RNA: North America, US: United States, RER: Europe. Further dataset-specific regions are detailed below.

Table 1 Geographies of the U.S. LCI Database Project.

NREL Category	ISIC Class (or Group/Division)	Geography
Crop Production / corn	0111	RNA, US
Crop Production / rice	0112	US
Crop Production / vegetables	0113	US
Crop Production / cotton	0116	US
Biomass / Planting, harvesting	0161	RNA
Forestry and Logging / Forest nurseries	0210	RNA, INW, PNW, SE
Forestry and Logging / Logging	0220	RNA, NE-NC, INW, PNW, SE
Mining (except Oil and Gas) / hard coal	0510	RNA
Mining (except Oil and Gas) / lignite	0520	US
Oil and Gas Extraction / Crude oil	0610	RNA
Oil and Gas Extraction	0620	RNA, US

Mining (except Oil and Gas) / uranium	0721	US
Mining (except Oil and Gas) / Bauxite	0729	GLO
Mining (except Oil and Gas) / limestone	0810	US
Biomass / Grinding (wet corn milling)	1062	RNA
Wood Product Manufacturing: Sawmilling and planing	1610	INW, NE-NC, SE, E, PNW
Wood Product Manufacturing: Veneer	1621	RNA, US, SE, E, PNW
Paper Manufacturing / Corrugated product	1702	US
Petroleum and Coal Products Mnf / Petroleum refining	1920	US
Chemical Manufacturing	2011	RNA, RER, US
Chemical Mnf. (Plastics material and resin mnf.)	2013	US
Plastics Product Manufacturing	2220	RNA, US
Glass and glass product manufacturing	2310	US
Nonmetallic Mineral Product Mnf. / cement, quicklime	2394	US
Primary Metal Manufacturing / iron, steel	2410	RNA, US
Primary Metal Manufacturing / alumina	2420	GLO, RNA, US
Fabricated Metal Product Manufacturing	2511	RNA
Elec. Equip., Appliance, and Comp. Mnf	2640	GLO
Utilities / Electricity	3510	RNA, US, Grids and eGrids
Utilities / Steam and airconditioning supply	3530	US, NE-NC, SE
Waste Management and Remediation Service / collection	3811	RNA, US
Transportation Equipment Manufacturing	4520	RNA
Transit and Ground Passenger Trans. / Urban and suburban passenger land transport	4921	US, Central, Alaska, Hawaii, ENC, NE, NW, S, SE, SW, W, WNC
Transit and Ground Passenger Trans. / Other passenger land transport	4922	US, Central, Alaska, Hawaii, ENC, NE, NW, S, SE, SW, W, WNC
Truck Transportation	4923	US, Central, Alaska, Hawaii, ENC, NE, NW, S, SE, SW, W, WNC
Water Transportation / Sea and coastal freight transport	5012	US
Water Transportation / Inland freight transport	5022	US
Air Transportation / Freight	5120	US
Rail Transportation	Group 491	US

The NREL database is a collection of data from various, already existing databases. Most processes are averages over either the US or North America (RNA). This includes virtually all processes that belong to the large categories Production of Chemicals, Biomass and Crop Production. For Crop Production the database mainly contains data which is extrapolated to the year 2022 and is averaged over RNA. Mining is also mainly US specific with the exception of Bauxite which is global. Categories which are more detailed spatially are Electricity, Forestry and Logging/Wood Product Manufacturing (anything to do with

wood), as well as Transportation. It is important to note that these sectors are subdivided into regions of the US of which some are unique to these types of data (e.g. forestry regions).

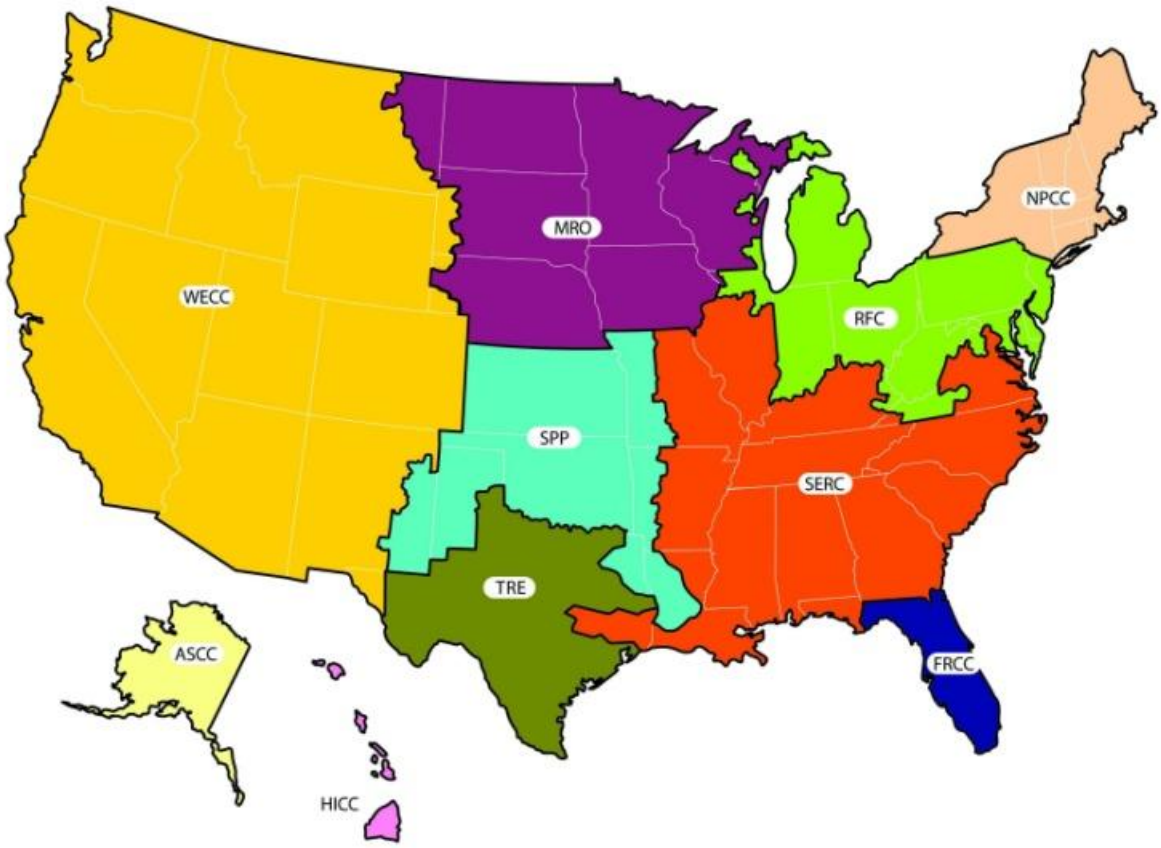

Figure 1 Electricity Administrative Regions: US Grids. Source: NERC grids, Accessed: 17.08.2014.

Electricity (ISIC 3510) is stored per Grid and eGrid. Grids have their own geographic regions. For example ERCT includes most of Texas but some border-regions belong to other grids. They do not always follow geographical boundaries as they are based on companies. eGrids represent smaller subdivisions of the North American Electric Reliability Corporation (NERC) regions (for example MRO West and MRO East).

Forestry and logging (ISIC division 02) and wood product manufacturing (div. 16) are divided into the same geographical regions. They appear to be subdivisions which include multiple states, not necessarily following state boundaries. In fact they correspond to important forestry regions in the US (U.S. Forest Service, Accessed: 17.08.2014). The divisions are: NE-NC (North-East, North-Central), INW (Inland West), E (Eastern US), PNW (Pacific North-West) and SE (South East). All the data connected to Forestry and Wood Products were collected by the Consortium for Research on Renewable Industrial Materials (CORRIM)(CORRIM, Accessed: 17.08.2014) and made available through NREL. The division into forestry regions is thus a CORRIM convention and is kept in the NREL database.

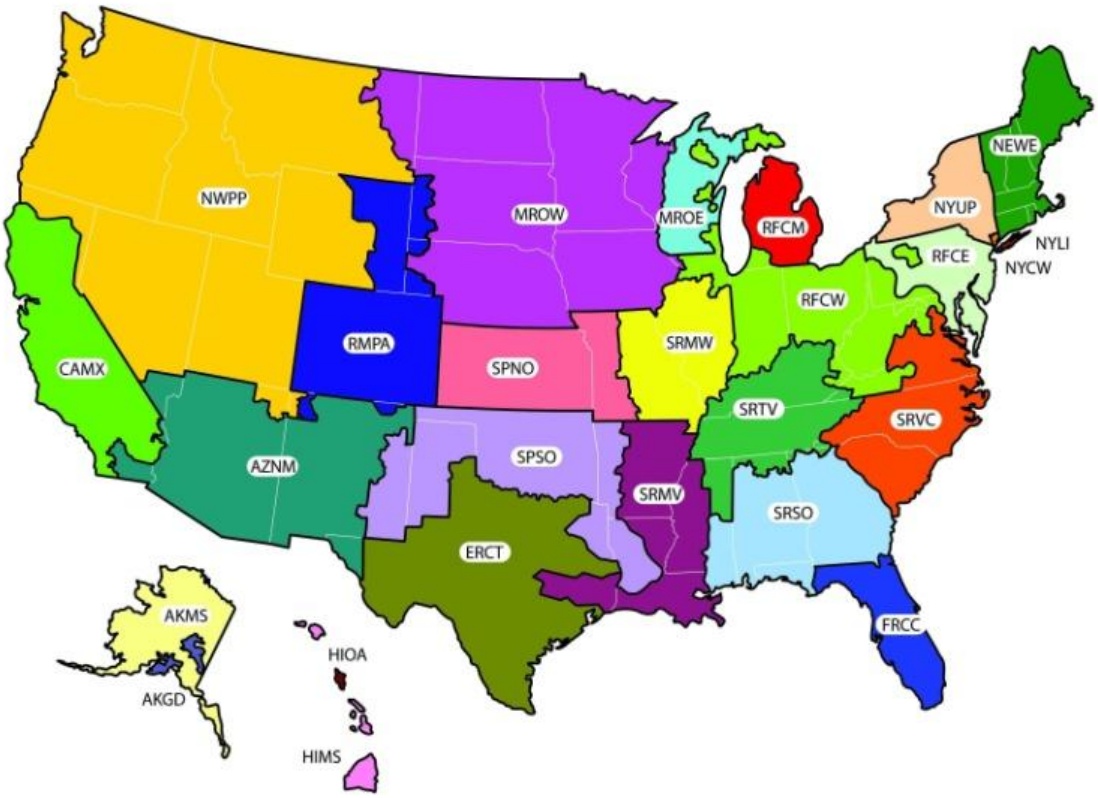

Figure 2 Electricity Administrative Regions: US eGrids. Source: eGrids, Accessed: 17.08.2014.

Various forms of transportation are included in the database. Transportation by sea and air as well as land transport with the exception of trucks and busses are only available as US averages. Most forms of truck (ISIC 4923) and bus transportation (ISIC 4921) are however divided into regions similar to those for forestry above but not identical. These regions correspond exactly to a set of states which is listed in the database, Alaska and Hawaii having their own regions: Alaska, C (Central), ENC (East-North-Central), Hawaii, NE (North-East), NW (North-West), S (South), SE (South-East), SW (South-West), WNC (West-North-Central), W (West). Transport which is divided into these regions is also available as US average.

3.2 ELCD

The European reference Life Cycle Database (ELCD) contains LCI data for the production of materials, energy carriers, transport and waste management. The datasets are provided by different industry associations. As the name implies, this database contains information on Europe and European countries only. The LCI Method Principle used is attributional, like NREL (ELCD, Accessed: 17.08.2014).

The data-classes into which the ELCD data is categorized correspond to neither ISIC nor CPA. The ISIC division or class was discerned as accurately as possible, sometimes with the need of separating ELCD categories.

Abbreviated geographical regions used: Same as NREL, additional regions defined below.

Table 2 Geographies of the ELCD.

ELCD Category	**ISIC Class (or Group/ Division)**	**Geography**
Mat. Production / other minerals / sand, gravel, kaolin	0810	RER, EU-27
Material Production / Wood	1610	DE
Systems / Construction / particle board	1621	EU-27
Energy carriers and technologies (crude oil based fuels), Energy carriers and technologies (Lignite + Hard coal based fuels)	1920	EU-15, EU-27
Energy carriers and technologies (mechanical energy), Mat. Prod. / Organic chemicals, Mat. Prod. /Inorganic chemicals	2011	GLO, RER, EU-27, EU-15
Mat. Production / Plastics	2220	RER
Mat. Prod. /Glass and ceramics / glass fibres	2310	RER
Systems / Construction / concrete blocks	2391	RER
Mat. Production / other minerals	2394	EU-27, RER, DE (->gypsum)
Mat. Prod. / Metals and semimetals / steel	2410	GLO
Mat. Prod. / Metals and semimetals / copper, aluminium, lead	2420	GLO, RER, EU-15, DE
Energy carriers and technologies (electricity)	3510	EU-27, RER, UCTE, Country
Energy carriers and technologies (Natural gas based fuels)	3520	EU-27
Energy carriers and technologies (Heat and Steam)	3530	EU-27, Country
Material Production / Water	3600	RER
End-of-life treatment (waste water treatment)	3700	EU-27, RER
End-of-life treatment (energy recycling, landfilling)	3821	EU-27
Transport services / Rail	4912	GLO, RER
Transport services / Road, Other transport	4923	GLO, RER
Transport services / Water / Bulk carrier, container ship	5012	GLO, RER
Transport services / Water / Barge	5022	GLO, RER
Transport services / Air	5120	GLO, RER
Systems / Packaging	8292	EU-27, EU-25

Most unit process data available in the ELCD is averaged over a set of European countries. The largest coverage is RER which defines the continent of Europe and therefore all countries located on it. EU-15 includes the countries which were part of the European Union before May 2004, hinting at an older dataset. EU-25 covers the 25 countries which have been part of the EU since May 2004, EU-27 since 2007. With Croatia joining in July 2013 the EU currently numbers 28 countries. The datasets have not yet been updated to include this spatial unit. It is important to note that Switzerland is only included in RER and not EU-15 or EU-27.

There are very few categories that include unit processes with a spatial resolution smaller than Europe or the EU. The unit processes which describe the creation of steam using either oil or natural gas are stored for each country within Europe. The same goes for electricity consumption mix at consumer level which, for each European country, is stored in the two categories 230V (amount varies slightly between countries) and 1kV-60kV. The categories <1kV and 1kV-60kV are also available for UCTE (Union for the Co-ordination of Transmission of Electricity) which contains continental Europe. Certain categories contain processes only available for Germany (DE). These are: Lead production (Metals and semimetals), Gypsum products (Other Minerals, Construction) as well as the processes in the category Material Production / Wood. It is interesting that this category is made up of only German data. Other data must not be easily available and Germany must be one of the fore-runners of LCI data collection.

3.3 ProBas

"Prozessorientierte Basisdaten für Umweltmanagement-Instrumente" (Process oriented basis data for environmental management tools) (ProBas) is a joint project between the Bundesamt für Umwelt (German federal office for environment) and the Öko-Institut e.V., a non-profit association dedicated to sustainable development. The goal of ProBas is to provide public access LCI process data for businesses, schools and consultants to assess product life cycles (ProBas, Accessed: 17.08.2014).

The ProBas library of life cycle data contains over 8000 processes which have been amassed from publicly available data sources. The database structure isn't very intuitive, again probably due to different data sources. The data isn't classified according to ISIC or CPA, class assignment is based on personal interpretation. ProBas categories were translated from German.

Abbreviated geographic regions used: Same as NREL. Additional country codes are defined here: http://www.gabi-software.com/support/gabi/geographical-codes/ (Accessed: 17.08.2014). Where processes exist for more than three individual countries these are combined to "Country".

Table 3 Geographies of the ProBas database.

ProBas Category	ISIC	Geography
Food: Cereals	0111	N/S/W-RER, Country, DE*
Food: Vegetables	0113	N/S/W-RER, RER, DE
Growing of cotton	0116	CN, US, PE*

Food: Animal feed / Growing of grass	0119	N/S/W RER, RER, Country
Food: Fruit	0121,0122,0123,0124,0125,0126	GLO, RER, DE
Growing of strawberries	0125	RER
Keeping of animals: Cattle	0141	N/W/S-RER, RER
Keeping of animals: Pigs	0145	N/W/S-RER, RER
Keeping of animals: Poultry	0146	N/W/S-RER, RER, DE*
Wood: Logs	0220	DE
Food: Ocean fishing	0311	GLO, RER
Mining: Hard coal	0510	Country
Mining: Brown coal	0520	Country
Petroleum: Extraction	0610	Country
Natural gases: Extraction	0620	GLO, RER, Country
Mining: Uranium	0721	GLO
Quarrying: Natural stones	0810	GLO, W-RER, RER, RNA, DE, CZ
Food: Meat production	1010	RER, DE*
Food: Pommes frites	1030	RER
Food: Oils (vegetable)	1040	RER, Country
Food: Dairy products	1050	RER, DE
Grinding of food products	1061	RER, DE
Food: Bread production	1071	RER, DE
Food: Sugar	1072	RER, DE, BR
Food: Pasta	1074	DE
Food: Frozen meals	1075	DE
Production of coffee	1079	DE
Production of spirits	1101	DE
Production of wines	1102	DE
Production of beer	1103	DE
Weaving of cotton	1312	CN, DK*, IT
Wood: Sawmill products	1610	DE, US, ID
Wood: Window frames	1622	DE
Manufacture of paper	1701	RER, DE
Processing of brown coal, hard coal	1910	RER, DE, CZ
Processing of brown coal, hard coal, petroleum	1920	GLO, RER, Country, Rheinisch/Leipzig/ Lausitz
Basic chemicals	2011	RER, DE, Country
Basic chemicals: Fertilizer	2012	DE
Plastic products	2013	GLO, RER, DE
Material production: Glass	2310	GLO, RER, DE, CN
Material production: Ceramics, roof tiles	2393	GLO, DE
Material production: Cement, lime, plaster	2394	RER, Country
Metals: Iron and Steel	2410	GLO, RER, Country
Basic chemicals: Ores and metals	2420	GLO, GLO-W, RER, Country
Silica wafer/module/cell	2610	DE

Manufacture of bikes	3092	DE, CZ
Electricity	3510	GLO, RER, EU-10 to EU-30(incl CH and NR) RER, Country, Per Plant (DE, MA, CZ)
Natural gases: Processing	3520	RER, Country
Heat	3530	RER, rheinisch/Leipzig/Lausitz
Wholesale of food products	4721	RER, DE
Transport: Rail: Passengers	4911	DE, CZ
Transport: Rail: Freight	4912	DE, CZ
Transport: Urban bus	4921	GLO, DE, CZ, TZ
Transport: Overland bus, passenger car	4922	GLO, DE
Transport: Lorry	4923	GLO, Country
Transport: Pipeline	4930	Country
Transport: Boat: Freight	5012	GLO, Country
Transport: Aeroplane: Passengers	5110	DE
Transport: Aeroplane: Freight	5120	DE, US
Frozen food storage	5210	RER, DE

*For this country there exists an ecological variant process.

The ProBas database contains a vast amount of process data with a focus on Germany and the German market. Numerous processes are also available for other countries. These were probably included in the database as they have a relevance for German companies which import these resources that were sourced elsewhere.

Agricultural processes are available on a variety of geographical levels. Animal production of cattle and pigs is only assessed over Northern/Western/Southern Europe and not per country whereas raising of poultry is also detailed for Germany and even includes a dataset for the ecological variant. There are also ecological variants for some processes in class 0111 but only for Germany and an ecological production of cotton for Peru in class 0116. It can be expected that these ecological variants will gain more and more importance in the future and a separate unit process for their production is essential as input and output, mainly due to lack of pesticides, are different.

Fruit production, with the exception of strawberries, is only available as an average over all kinds of fruit and therefore corresponds to multiple ISIC classes.

Germany is the world's leading producer of lignite (brown coal) (World Coal, Accessed: 17.08.2014). It is therefore not surprising that data connected to lignite, in this case the manufacture of briquettes from lignite as well as the generation of steam (and in further extent electricity) using lignite as fuel, are available for different geographic regions. In ProBas these regions are divided into Rheinisch (Rhineland), Leipzig and Lausitz. From the description of the data one could interpret the datasets from Lausitz and Leipzig to be at-plant and therefore site-specific, but it is somewhat ambiguous.

The Land Transport division contains one of the most extensive datasets contained in ProBas with differentiations between processes in categories such as vehicle model, fuel type, capacity utilisation and emission standard. Geographically the differentiation is not very detailed, including generic datasets (GLO) and for a row of different countries, with most processes belonging to Germany. It is arguable if a higher geographic specificity would be of much benefit for this kind of process as the spatial influence is likely outweighed by the other factors. The only geographical factor of much significance here would be Topography, as the fuel for a transport of goods or people for a kilometre would also depend on the terrain. Geographical categories based on average road inclination would be hard to implement.

3.4 Netzwerk Lebenszyklusdaten

The Netzwerk Lebenszyklusdaten (Network for Life Cycle Data) was a project which was supported by the German federal ministry for education and science between 2003 and 2008. It should provide the scientific basis for data collection for the use in attributional LCAs (Netzwerk Lebenszyklusdaten, Accessed: 17.08.2014). Developers of the Netzwerk Lebenszyklusdaten went on to work on the BioEnergieDat database (BioEnergieDat, Accessed: 17.08.2014), another public access life cycle database, which wasn't included as an additional database in this paper due to the lack of variance in spatial specificity (all processes are averaged over Germany).

The datasets in the Netzwerk Lebenszyklusdaten database all concern themselves with either materials for the construction industry or transport and so the classification results in only a very limited number of classes. The data is classified using the ILCD format and manually assigned to ISIC classes.

The abbreviated geographic regions used are identical to ProBas.

Table 4 Geographies of the Netzwerk Lebenszyklusdaten database.

Netzwerk Lebenszyklusdaten	ISIC	Geography
Systems: Building and Transport Infrastructure: Gypsum, Anhydrite, Sand, Gravel	0810	DE
Systems: Building and Transport Infrastructure: Cement	2394	DE
Materials Production: Metals and Semimetals: Steel	2410	GLO
Transport services / Rail: Passengers	4911	DE
Transport services / Rail: Freight	4912	DE
Transport services / Water: Freight: Inland	5022	DE
Transport services / Air: Passengers	5110	DE
Transport services / Air: Freight	5120	DE

Almost all data in Netzwerk Lebenszyklusdaten database are averages over Germany. The sole exception is ISIC category 2410: Manufacture of basic iron and steel, which here includes a single dataset from the International Iron and Steel Institute which provides global data.

What is unique for the datasets used here is that for freight transport by rail there is differentiation between flat, hilly and mountainous regions. This means the geographic factor of topography is taken into account but without geographical context, as the location of these regions is undefined. These regions would have to be classified when deciding which data to use for an LCA, for example using a geographic information system (GIS) to define the boundaries between regions with different terrain.

3.5 AusLCI

The Australian National Life Cycle Inventory Database (AusLCI) is a project by the Australian Life Cycle Assessment Society (ALCAS). Its goal is to provide a publicly accessible database which grants transparent environmental information for every step of a product's life cycle. It is intended for use by anyone wanting to do an LCA by providing data and guidelines for collecting other data needed. It will allow companies to compare benchmarks and assess measures to improve them. The Australian government could find the data useful for policymaking (AusLCI, Accessed: 17.08.2014).

The process data is not classified according to ISIC or CPA. The Processes are manually allocated to ISIC classes.

The abbreviated geographic regions used are:

GLO: Global, AU: Australia, QLD: Queensland, NSW: New South Wales, NT: Northern Territory, EU-15: European Union - 15 members.

Table 5 Geographies of the AusLCI database.

Process Name	ISIC	Geography
Barley, Canola, Lupins, Maize, Wheat, Sorghum	0111	AU, low rainfall zone South AU, medium rainfall zone South AU, high rainfall zone South AU, North East NSW*, North West NSW, central west NSW, central east NSW, Great Southern region WA, Darling Downs QLD, Central QLD, northern Victoria, Keller-berrin Western AU, Narrogin Western AU
Broccoli, Lettuce, Potato, Tomato	0113	Lockyer Valley, Burdekin QLD
Sugar Cane	0114	Average QLD, Bundaberg QLD, Burdekin QLD, Herbert QLD, Mackay QLD, wet tropics QLD
Cotton	0116	AU, Central cotton growing zone, northern zone, southern zone
Avocado, Banana	0122	Brisbane Moreton QLD, wet tropics QLD
Almonds, Strawberries	0125	South AU, Brisbane Moreton QLD
Capsicum	0128	Burdekin QLD
Airblast crop spraying / bed forming / irrigation	0161	AU, QLD, South AU, NSW
Vaccination of cows	0162	AU
Cotton ginning	0163	AU
Canola Oil, Cottonseed Oil	1040	GLO, AU
Bagasse	1061	AU
Gluten, Wheat Starch	1062	AU
Molasses	1072	AU
Growth promotant feed	1080	AU
Hardwood and softwood timber, sawlogs, veneer, chips	1610	AU
Ethanol	2011	AU
Electricity: high / low voltage	3510	AU, Eastern AU, NSW, NT, QLD, South AU, Tasmania, Victoria, Western AU
Collection and processing of aluminium / steel scrap	3811	AU
Waste treatment at Landfill, Methane combustion	3821	AU, NSW, South AU, NT, QLD, Tasmania, Victoria, Western AU
Recycling Aluminium	3830	AU
Irrigation infrastructure	4220	AU
Transport: Freight Rail	4912	AU, EU-15
Transport: Freight Road	4923	AU
Transport: Passenger Air	5110	AU
Transport: Freight Air	5120	AU

Processes in AusLCI are either averaged over the entirety of Australia or over different sized subsets, on state level and below.

The AusLCI data is very spatially specific in many classes belonging to division 01. In class 0111 it contains processes which are representative for as many as 15 different regions in total. Notable are the subdivisions of Australia's larger states. South Australia is divided into three zones of different rainfall. If this is based on certain yearly averages is not specified. For New South Wales five agricultural zones are used: North East, North West, Central West, and Central East. There are a number of far smaller regions specified for Western Australia and especially for Queensland (6 local government areas).

Electricity mixes and differentiations between high and low voltage are represented with a dataset for each Australian state. As methane combustion is used to generate electricity it is divided into the same regions, just as electricity production through usage of coal and natural gas, but is classified as treatment and disposal of non-hazardous waste in ISIC despite this fact.

3.6 USDA

The LCA Digital Commons project by the United States Department of Agriculture (USDA) is intended to provide unit process data for LCAs of bioproducts such as food and biofuel which are produced in the United States. The database focuses exclusively on crop production (ISIC classes 0111, 0112 and 0116) but also includes data belonging to other classes which are relevant as inputs and outputs (e.g. production of fertilizer) (USDA, Accessed: 17.08.2014).

The USDA LCA Digital Commons database is classified in ISIC categories.

The abbreviated geographic regions used are identical to ProBas.

Table 6 Geographies of the USDA LCA Digital Commons database.

Class Name	ISIC class	Geography
Growing of cereals (except rice), leguminous crops and oil seeds	0111	US States
Growing of rice	0112	US States
Growing of fibre crops	0116	US States
Support activities for crop production	0161	CH
Quarrying of stone, sand and clay	0810	RER, CH
Manufacture of fertilizer and nitrogen compounds	2012	RER
Manufacture of pesticides and other agrochemical products	2021	RER
Water collection, treatment and supply	3600	RER
Sewerage	3700	RER

Treatment and disposal of non-hazardous waste	3821	RER
Freight rail transport	4912	US
Freight transport by road	4923	RER
Sea and coastal freight water transport	5012	Oceanic

The database contains state-averaged unit processes for ISIC classes 0111, 0112 and 0116, allowing for state specific LCAs.

Classified amongst the remaining ISIC classes listed are such processes as fertilizer and pesticide production, as well as the materials needed for this (Dolomite, gypsum etc.). There is a dataset per state given but these are crosswalks between LCA Commons data and ecoinvent data. Operations in the whole of US or EU / Switzerland are used as surrogates and the datasets therefore identical for each state. In the descriptions of the datasets it is mentioned that geographic representativeness is reduced as a result of this crosswalk. A higher spatial resolution of the ecoinvent database would prevent this reduction. Alternatively, independence from ecoinvent data could be reached through better local data, which according to the LCA Digital Commons website (USDA, Accessed: 17.08.2014) is under development and listed as Phase 2 (Irrigation, manure management, and farm equipment operation) and Phase 3 (Mineral, fertilizer, herbicide, insecticide, and fungicide data) of the project.

3.7 NEEDS

The New Energy Externalities Development for Sustainability (NEEDS) LCI database contains data which concerns the future electricity supply systems. This means its focus is on process data involving new energy technologies such as solar, wind, wave and advanced fossil fuel energy production. It also contains data on future transport systems and material supply. The data is intended for use in long-term assessments (NEEDS, Accessed: 17.08.2014).

The data isn't classified using the ISIC or CPA format and was assigned to ISIC classes manually. Due to the large majority of unit processes being assigned to the wide ISIC class 3510, an additional differentiation between technologies was included, as these are relevant for the spatial specificity of the processes.

The abbreviated geographic regions used are identical to ProBas except UCTE: Union for the Coordination of Transmission of Electricity (Electricity grid for continental Europe).

Table 7 Geographies of the NEEDS database.

NEEDS	**ISIC**	**Geography**
Mining: Hard coal	0510	RER
Mining: Iron	0710	GLO
Mining: Aluminium, copper, nickel	0729	GLO, RER, RLA
Manufacture of glass	2310	RER

Manufacture of clinker	2394	CH
Electricity production mix	3510	UCTE
Electricity: Fuel cells	3510	DE
Electricity: Hard coal	3510	RER
Electricity: Lignite	3510	RER
Electricity: Natural gas	3510	RER
Electricity: Nuclear	3510	UCTE
Electricity: Photovoltaic	3510	Central/N-RER
Electricity: Solar thermal	3510	MA
Electricity: Wave energy	3510	RER
Electricity: Wind power	3510	DK
Electricity: Wood energy	3510	RER
Hydrogen	3520	RER
Transport: Freight road	4923	RER, CH

Most unit processes are averaged over Europe while some more uncommon forms of generating electricity are specified for a certain country where appropriate power plants exist. Fuel cells data is from Germany, solar thermal data from Morocco and wind energy data from Denmark. Processes relevant to the construction and operation of power plants are the mining of coal, and various metals whose datasets are averaged globally, over Europe or Latin America. Ecoinvent data is used for some processes, which becomes evident as manufacture of clinker and freight road transport contain Swiss averages.

3.8 ecoinvent

Ecoinvent was founded by Swiss universities and research institutes aiming to create a comprehensive LCI database whose use goes beyond Switzerland. Ecoinvent now hosts the world's leading international LCI database with high quality datasets (ecoinvent, Accessed: 17.08.2014).

As mentioned above, ecoinvent provides an overview xls file which lists unit processes classified using ISIC, including the geography of each process. This is a good basis for a quantitative analysis of the data. The geographies used by ecoinvent, listed and explained in a separate file, have been divided into levels of spatial specificity detailed in the next section. I wrote a program which parsed the overview file and assigned the unit processes their respective levels. The output is a table which for each ISIC class details the number of processes it contains, the percentage of unit processes belonging to each geographical level as well as the most common level amongst unit processes to allow a quick overview. It is noteworthy that the ecoinvent overview file contains processes which are not assigned to ISIC classes but instead to groups or divisions (as ISIC doesn't contain an adequate class). This means the mentioned numbers are also calculated for these levels but only represent the unassigned processes.

The resulting table can be found in the appendix (**Table 9 (Appendix)**) and will be used in the discussion which follows.

4. Comparison and Discussion

Geographic representation is one of several data quality indicators. In the paper by Rousseaux et al. (2001) it is mentioned as a Quality Component alongside Time-related Representativity and Technology. Representativity refers to a certain process. Other Quality Indicators are Justness (Flow), Completeness (Process), Repeatability (System) and Uncertainty (Flow/System). In certain Quality Assessments only Uncertainty is used or the qualitative components are used to calculate uncertainty. This is rather limiting, especially when regarding the fit to the objective of study. Data quality scores can be used to summarize all the Quality Components.

Geographical Representativity can be split up into 5 different scores, according to Rousseaux et al. (2001):

1. Data in direct relation with the area of study

2. Average data from larger area in which the area under study is included

3. Data from different area with similar production conditions

4. Data from area with slightly similar production condition

5. Data from unknown area or area with very different production conditions

As we are not in the process of doing an LCA and this paper seeks to provide an overview of unit process spatial specifity in different LCI databases, we are in need of a different classification system which in some way still reflects the data quality aspect "geographic representation". The method closest to hand is the use of country and continent boundaries to define different levels of spatial specificity. However, it is worth first taking a look at the way geographic representation is specified in the data before deciding on what levels make sense for a comparison.

Geographic regions represented in the data can be divided into the following categories:

- Generic or Global (GLO)
- Groups of multiple countries (e.g. RNA, RER, EU-15, EU-25)
- Countries (e.g. CH, DE etc.)
- Subdivisions of countries (e.g. States, electric Grids)
- Site-specific (e.g. power plant Dukovany in CZ)

The biggest shortfall these levels contain is the varying area of the spatial units. The level "Countries" for example contains the US as one spatial unit and CH as another which is hierarchically equivalent although its area is so much smaller. The same goes for "Groups of multiple countries" where EU-15 is a subset of EU-25 for example. Alternatives to these levels are not trivial to implement. A possibility would

be levels strictly based on area in km^2. For this study I choose to accept the shortcomings of this country-oriented level design for the lack of an efficient alternative and the fact that this study should merely provide an overview of spatial specificity for which these levels are adequate.

We thus arrive at 5 levels of spatial specificity (representivity):

1. Global
2. Groups of countries
3. Individual countries
4. Regions within countries
5. Site-specific

4.1 Spatial Specificity of the ISIC Classes

The table which includes the levels per ISIC class and database and on which part of this discussion is based can be found in the appendix (**Table 8 (Appendix)**). As certain ISIC classes are only represented in one database (ProBas contains many processes the others do not) there are many empty fields. The discussion will focus on classes where there are multiple entries for comparison.

The discussion will focus on ISIC divisions whose unit process data either shows a consistency regarding its spatial specificity over different databases or where there are clear differences in regionalisation between databases. To provide some structure to the discussion it is divided into ISIC divisions (or multiple similar ISIC divisions), and each part will focus on the classes contained within those divisions. Not all ISIC divisions are included in the discussion for a number of reasons: There are numerous divisions that are not represented in the analysed databases or only in one database which makes a comparison impossible. Other divisions contain classes where no clear pattern can be identified and no conclusive statement made. For a detailed look at the spatial specificity levels for each class and database the tables are provided as reference.

Division 01: Crop and animal production, hunting and related service activities

In the section about geographical factors we noted that Agriculture, especially crop production, is one of the most spatially dependant categories. In order to create accurate LCAs based on this data, a high spatial resolution is therefore desirable, although this also depends on the spatial variability of climate and soil in the regions of interest.

Databases which aren't primarily focussed on agricultural processes do not contain data of spatial specificity level higher than 3 (NREL, ProBas, ecoinvent unless specified further in the full database). They do however provide country averages. NREL is solely US focussed and provides US averaged data . ProBas is Germany centric but includes data for many countries except for class 0113 (vegetables) which is only

available for DE. Notable is the lack of global agricultural datasets in both NREL and ProBas. ProBas contains global data for fruit but no other crops while NREL contains no global data for div. 01. Meanwhile, in ecoinvent clearly more than 50% of data in div. 01 is global. This shows that ecoinvent is internationally oriented, while NREL and ProBas are only intended for use in their respective countries.

Ecoinvent also provides processes for a row of countries, with Swiss datasets available for most crops which are produced in Switzerland. There are only two processes in div. 01 that are averaged over Europe and none for other groups of countries (level 2). LCAs for crops produced in European countries not included in ecoinvent must therefore either use datasets from other countries (e.g. Switzerland), create an average between these countries or use the global dataset, the last of which is likely to be the most inaccurate. The growing of various fruits are only available as global datasets.

Data of higher spatial specificity (level 4) is available from USDA and AusLCI. The USDA database includes processes for ISIC classes 0111, 0112 and 0116 and provides this data averaged per U.S. state. Support activities for crop production (0161) are taken from the ecoinvent Swiss averages. AusLCI also includes mostly level 4 data averaged over Australian states with some processes associated with more specific regions like local government areas. The availability of more specific processes is likely coupled with demand for these, as the U.S. and Australia both cover vast areas with regionally very differentiated climates. Classifications into different rainfall zones in South Australia for example is not necessary for the moderate climate of Europe.

From this analysis we can gather that large LCI databases which cover a wide range of process data usually contain div. 01 data with spatial specificity level 3 and below. Large countries however call for more accurate data and have access to it through more specified databases (USDA) or by including spatially specific data in the country's main LCI database (AusLCI).

Division 02: Forestry and logging

Spatial differentiation of forestry and logging activities can be of use when taking into account that forest composition and structure is to some degree dictated by climate (boreal, tropical). The same process could potentially differ for different forest types, which could be solved by either creating more regionally specific averages or more differentiated thematic classifications (e.g. by tree type).

ProBas includes processes belonging to class 0220 (Logging) for each different tree type. The data is only available for Germany. NREL contains North American (level 2) and level 4 data for activities in classes 0210 (silviculture and other forestry activities) and 0220. The more specific classification into five forestry regions is possibly more on administrative grounds, by the data provider (CORRIM, Accessed: 17.08.2014) but could still be relevant for LCAs. Ecoinvent contains processes for all div. 02 classes. The data is mostly global and European averaged (levels 1 and 2) with a few country-level exceptions where specific tree-types are concerned (e.g. eucalyptus, meranti).

The spatial specificity of processes in this division seems to vary largely between databases. The NREL approach is the most consistent within the database, providing the data for each forestry region as well as over RNA. It is not clear if this benefits LCAs much, and the ecoinvent approach might be more efficient.

Divisions 05, 06, 07, 08, 09: Mining and quarrying

The location of mines and where resources originate is not only relevant for transportation but also because mining practices and the technologies used can vary from country to country.

Coal mining is assessed on levels 1, 2 and 3. Ecoinvent contains country specific data for hard coal (class 0510) but only level 1 and 2 data for lignite (0520) while NREL possesses RNA data for hard coal and more specific (US) data for lignite. ProBas has country specific data for both types of coal. Country-level data of the largest coal producing countries (World Coal, Accessed: 17.08.2014) would be most helpful for LCAs. These are included in ProBas and partly in Ecoinvent (only for hard coal) but not in NEEDS.

Petroleum (0610) and natural gas (0620) data is available for an array of countries in ProBas. Ecoinvent has data on levels 1, 2 and 3, the country level representing the most important producers of crude petroleum and gas. NREL has petroleum data for RNA and natural gas data for RNA and US.

Mining of iron (0710) processes are found in NEEDS and ecoinvent and are all global except one RER level 2 averaged process (portafer) in ecoinvent. Mining of uranium and thorium ores (0721) is US averaged in NREL, global in ProBas and globally and RNA averaged in ecoinvent. Other non-ferrous metals (0729) are level 1 and 2 averaged in NREL and NEEDS but listed for various countries in ecoinvent. Processes involving mining of iron, uranium and thorium ores are thus spatially rather unspecific over all the analysed databases. For other non-precious metal ores ecoinvent provides more spatially detailed data.

Ecoinvent contains processes in all classes of div. 08 (Other mining and quarrying) while the other databases only include the quarrying of stone, sand and clay (0810). The extraction of peat (0892), salt (0893) and other mining and quarrying n. e. c. (0899) are all rather spatially unspecific, averaged over levels 1 and 2. Stone, sand and clay are more specific, with NREL, ProBas, Netzwerk Lebenszyklusdaten, USDA and ecoinvent including level 3 data. As the quarrying of stone, sand and clay is a common process, there is more higher quality data available which allows individual countries to provide country-averaged data while the other processes have to be averaged over larger areas.

Mining and quarrying activities possess spatial specificity levels of 1, 2 and 3 across all databases. The differences in levels across databases seems somewhat arbitrary. However, we could identify that the mining of iron and uranium is not as regionalised as the mining of other ores and that the mining of stone, sand and clay as well as the mining and extraction of the fuel resources coal and petroleum, are the most spatially specific.

Divisions 10, 11: Manufacture of food and beverage products

The manufacture of food and beverages is geographically dependant only on the sourcing of the materials needed. Nevertheless, most food and beverage producing processes in the ProBas and AusLCI databases are country-specific (level 3). ProBas has most of these processes averaged over Germany, AusLCI over Australia. However, in ProBas like ecoinvent, more specialised food production like sugar (1072) is averaged over a single manufacturing country (e.g. Brazil).

The manufacture of food and beverages is often stored in a country-level and a spatially more unspecific variant. For ProBas this is usually RER and DE, for ecoinvent GLO and CH (plus other countries for specific products).

Division 16, 17: Manufacture of wood and wood products (except furniture), manufacture of paper

The manufacture of wood and wood products is tightly connected to forestry and logging, which is evident when looking at the NREL database. Processes in this division are also averaged over forestry regions. This kind of regionalisation is not found in the other databases. ProBas provides data averaged over Germany and no other countries and ELCD also includes only German averaged data. The large majority of div. 16 processes in ecoinvent are not spatially specific (levels 1 and 2) with some country-specific processes for Brazil (Sawmilling and planing of wood, 1610) and Switzerland (Manufacture of veneer sheets and wood-based panels, 1621). Paper manufacturing is stored on similar levels.

Regionalisation is just as diverse when it comes to the manufacture of wood as it was with forestry and logging, due to the spatially specific classification of the NREL data.

Division 19: Manufacture of coke and refined petroleum products

Although ProBas does not include a special regionalisation for the mining of brown coal (lignite) it does so for the manufacture of coke and refined petroleum products from brown coal, more accurately the production of briquettes (1920). There are three main production regions (rheinisch, Lausitz and Leipzig). These three regions are probably differentiated due to the importance of the brown coal industry in Germany. The other databases don't include spatial specificity this high for any processes associated with div. 19, being instead averaged over the globe, Europe or individual countries (in the case of ecoinvent only around 15%).

Division 20, 23: Manufacture of chemicals and chemical products, manufacture of other non-metallic mineral products

Processes that have to do with the manufacture of chemicals and chemical products are diversely regionalised over the different databases. ProBas contains dominantly German processes while in ecoinvent and ELCD these kinds of processes are mainly global or European averages. Ecoinvent has no level 3 regionalisation for the manufacture of pesticides, soaps and paints (2021, 2022, 2023).

All databases containing ceramics as well as cement, lime and plaster production have processes which are averaged on country-level. On this level ecoinvent has a large amount of CH and US processes.

Division 24: Manufacture of basic metals

Just as with the mining of iron, the manufacture of iron and steel (2410) is a process which consistently has low levels (1 and 2 with rarely 3) of spatial specificity across the databases. Ecoinvent has 62% level 1 and 38% level 2 processes in this class. Similarly ecoinvent also has poor (7.8% level 3) regionalisation in the manufacture of basic precious and non-ferrous metals (2420), although ProBas does contain various country-specific data for this class.

Division 35: Electricity, gas, steam and air conditioning supply

Electric power generation, transmission and distribution (3510) is the only class with high regionalisation (level 4) over most of the analysed databases. In NREL the US is divided into NERC Grids and even more spatially specific eGrids (detailed in the NREL section). Ecoinvent uses the same NERC classification for the US (Grids but not eGrids). For countries other than the US ecoinvent contains level 3 data. In AusLCI electricity mixes are averaged over states, and in ProBas there are electricity-mix datasets for many countries, level 4 regionalised datasets for electricity produced from brown coal (the same regions as briquette production from brown coal) as well as the only datasets in this study that are detailed as being site-specific (level 5), from coal, petroleum and nuclear power plants.

The regionalisations of power grids seem to be a mainly administrative and exist where the power grids are very large. In the US this division of power grids is done by electricity companies. This could be the reason that there is data for multiple regions in countries with large areas like the US and Australia, but not for other countries.

Division 38: Waste collection, treatment and disposal activities, materials recovery

The treatment and disposal of non-hazardous waste (3821), which includes landfill activities is also one of the more regionalised classes with certain processes that have a spatial specificity of 4 in the AusLCI and ecoinvent databases. While in the AusLCI database the waste treatment at landfill is defined for

each Australian state, in ecoinvent the regionalisation is rather less systematic with only waste treatment in Canada being divided into more specific regions.

Division 49: Transportation and Storage

Road Transportation is characterised by very differentiated regionalisation between databases. On the one hand, we have statewise (level 4) regionalised transportation by road (4921, 4922, 4923) in the NREL database, and on the other ELCD datasets where road transport is averaged on levels 1 and 2 and ecoinvent datasets, where these levels of regionalisation also make up the vast majority. In between are country-specific processes of ProBas, AusLCI and NEEDS.

More similarities between the databases exist in rail transport (4911, 4912), where most datasets are regionalised on country-basis (level 3). Freight transport by sea is mostly represented by global datasets (100% level 1 in ecoinvent) and air transport is either level 1 and 2 (ecoinvent, ELCD) or level 3 (NREL, ProBas, Netzwerk Lebenszyklusdaten, AusLCI).

5. Conclusion

After an in-depth analysis and comparison of the spatial specificity of unit processes per ISIC division and database, there are a few concluding statements we can make about the overall situation regarding the regionalisation of processes.

When analysing the regionalisation within a single database, it often seems rather unsystematic. Some classes might contain heavily regionalised data while others have a very low spatial specificity. The reason for the regionalisation of one type of process over another is sometimes evident (e.g. agricultural data in AusLCI), but often this does not seem to be of any more significant benefit to LCAs (e.g. road transport and manufacture of wood products data in NREL). This is mainly because all of the LCI databases that were analyzed are publicly available, except ecoinvent, and cover a wide range of processes. The databases thus rely heavily on data provided by different businesses that have already gathered the LCI data relevant to their products and services. These databases can therefore be seen as a pool of LCI data where inconsistencies in regard to spatial specificity are a common occurrence due to multiple different data sources. To be more consistent, databases could create averages from more specific data, but the specificity of the data is more desirable than a consistently regionalised database. Alternatively, there could be regionalisation requirements introduced for each type of process in order to conform to a new ISO norm.

Another open question regarding regionalisation is that it is often difficult to tell if the data are regionalised due to the desire for higher spatial specificity or simply because it is the easiest way of collecting the data due to administrative reasons (e.g. manufacture of wood products in NREL).

These observations aside, we were also able to identify numerous ISIC classes which show higher or lower regionalisation across most databases. Notable examples for high regionalisation were crop production and electricity, whereas mining activities and production of metals, especially the mining of iron and the manufacture of iron and steel, show low regionalisation.

In this study, we focussed on the regionalisation of datasets in attributional LCI databases. An interesting field for further research regarding regionalisation would be the life cycle impact assessment phase of an LCA. Currently, the impact of outputs on the environment is still normally assessed on a global scale, which for CO_2 and Ozone may be adequate, but far from optimal for other environmental burdens like fertilizer. These are more regional and local in their effect and the sensitivity of the receiving environment is also spatially diverse. There are efforts to improve this, however it does add a lot of complexity to LCAs (Finnveden et al., 2009).

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Appendix

Table 8 (Appendix) Spatial specificity levels per database and ISIC class.

Database / ISIC Class	NREL	ELCD	ProBas	Netzwerk Lebens-zyklusdaten	AusLCI	USDA	NEEDS
0111	2, 3		2, 3		3, 4	4	
0112	3					4	
0113	3		2, 3		4		
0114					4		
0116	3		3		3, 4	4	
0119			2, 3				
0121			1, 2, 3				
0122			1, 2, 3		4		
0123			1, 2, 3				
0124			1, 2, 3				
0125			1, 2, 3		4		
0126							
0128					4		
0141			2				
0145			2				
0146			2, 3				
0161	2				3, 4	3	
0162					3		
0163					3		
0210	2, 4						
0220	2, 4		3				
0311			1, 2				
0510	2		3				2
0520	3		2				
0610	2		3				
0620	2, 3		1, 2, 3				
0710							1
0721	3		1				
0729	1						1, 2
0810	3	2	1, 2, 3	3		2, 3	
1010			2, 3				
1030			2				
1040			2, 3		1, 3		
1050			2, 3				

1061			2, 3		3		
1062	2				3		
1071			2, 3				
1072			2, 3		3		
1074			3				
1075			3				
1079			3				
1080					3		
1101			3				
1102			3				
1103			3				
1312			3				
1610	4	3	3		3		
1621	2, 3, 4	2					
1622			3				
1701			2, 3				
1702	3						
1910			2, 3				
1920	3	2	1, 2, 3, 4				
2011	2, 3	1, 2	2, 3		3		
2012			3			2	
2013	3		1, 2, 3				
2021						2	
2220	2, 3	2					
2310	3	2	1, 2, 3				2
2391		2					
2393			1, 3				
2394	3		2, 3	3			3
2410	2, 3	1	1, 2, 3	1			
2420	1, 2, 3	2, 3	1, 2, 3				
2511	2						
2610			3				
2640	1						
3092			3				
3510	2, 3, 4	1, 2, 3	1, 2, 3, 4, 5		3, 4		2, 3
3520		2	2, 3				2
3530	3, 4	2, 3	2, 4				
3600		2				3	
3700		2				3	
3811	2, 3				3		
3821		2			3, 4	3	

3830					3		
4220					3		
4520	2						
4721			2, 3				
4911	3		3	3			
4912	3	1, 2	3	3	2, 3	3	
4921	3, 4		1, 3				
4922	3, 4		1, 3				
4923	3, 4	1, 2	1, 3		3	2	2, 3
4930			3				
5012	3	1, 2	1, 3			2	
5022	3	1, 2		3			
5110			3	3	3		
5120	3	1, 2	3	3	3		
5210			2, 3				
8292		2					

Table 9 (Appendix) Geography percentages of the ecoinvent database.

ISIC Classification	Processes	Most common level	Level1 %	Level2 %	Level3 %	Level4 %
01:Crop and animal production; hunting and related service activities	11	3	45.45	0	54.55	0
0111:Growing of cereals (except rice); leguminous crops and oil seeds	189	1	58.73	1.06	40.21	0
0112:Growing of rice	3	1	66.67	0	33.33	0
0113:Growing of vegetables and melons; roots and tubers	60	1	91.67	0	8.33	0
0114:Growing of sugar cane	6	tied	50	0	50	0
0116:Growing of fibre crops	32	3	43.75	0	56.25	0
0119:Growing of other non-perennial crops	44	1	63.64	0	36.36	0
012:Growing of perennial crops	4	1	100	0	0	0
0121:Growing of grapes	2	1	100	0	0	0
0122:Growing of tropical and subtropical fruits	8	1	100	0	0	0
0123:Growing of citrus fruits	2	1	100	0	0	0
0124:Growing of pome fruits and stone fruits	4	1	100	0	0	0
0125:Growing of other tree and bush fruits and nuts	4	1	100	0	0	0
0126:Growing of oleaginous fruits	9	1	55.56	0	44.44	0
0129:Growing of other perennial crops	9	1	66.67	0	33.33	0
0130:Plant propagation	10	1	60	0	40	0
014:Animal production	3	1	100	0	0	0
0141:Raising of cattle and buffaloes	6	1	66.67	0	33.33	0
0144:Raising of sheep and goats	10	1	60	0	40	0
0145:Raising of swine/pigs	6	1	66.67	0	33.33	0
0161:Support activities for crop production	237	1	57.38	0	42.62	0
0162:Support activities for animal production	3	1	66.67	0	33.33	0
0163:Post-harvest crop activities	30	1	66.67	0	33.33	0
0164:Seed processing for propagation	88	1	72.73	0	27.27	0
0210:Silviculture and other forestry activities	26	1	61.54	23.08	15.38	0
022:Logging	4	1	100	0	0	0
0220:Logging	65	1	58.46	35.38	6.15	0
0230:Gathering of non-wood forest products	8	1	62.5	37.5	0	0
0510:Mining of hard coal	49	3	22.45	24.49	53.06	0
0520:Mining of lignite	11	1	54.55	45.45	0	0
0610:Extraction of crude petroleum	113	3	44.25	8.85	46.9	0
0620:Extraction of natural gas	54	3	44.44	3.7	51.85	0
0710:Mining of iron ores	7	1	85.71	14.29	0	0
0721:Mining of uranium and thorium ores	16	1	62.5	37.5	0	0

0729:Mining of other non-ferrous metal ores	187	1	56.15	15.51	28.34	0
0810:Quarrying of stone; sand and clay	96	1	61.46	10.42	28.12	0
0891:Mining of chemical and fertilizer minerals	28	1	67.86	10.71	21.43	0
0892:Extraction of peat	8	1	62.5	37.5	0	0
0893:Extraction of salt	10	1	60	40	0	0
0899:Other mining and quarrying n.e.c.	5	1	80	20	0	0
0910:Support activities for petroleum and natural gas extraction	12	1	100	0	0	0
0990:Support activities for other mining and quarrying	6	1	100	0	0	0
1010:Processing and preserving of meat	12	1	58.33	0	41.67	0
1040:Manufacture of vegetable and animal oils and fats	91	1	60.44	5.49	34.07	0
1062:Manufacture of starches and starch products	17	1	58.82	17.65	23.53	0
1072:Manufacture of sugar	31	1	54.84	0	45.16	0
108:Manufacture of prepared animal feeds	42	1	100	0	0	0
1311:Preparation and spinning of textile fibres	13	1	61.54	0	38.46	0
1312:Weaving of textiles	29	1	68.97	13.79	17.24	0
1391:Manufacture of knitted and crocheted fabrics	8	1	100	0	0	0
1399:Manufacture of other textiles n.e.c.	8	1	62.5	37.5	0	0
16:Manufacture of wood and of products of wood and cork; except furniture; manufacture of articles of straw and plaiting materials	3	1	100	0	0	0
1610:Sawmilling and planing of wood	159	1	55.97	40.88	3.14	0
1621:Manufacture of veneer sheets and wood-based panels	134	1	59.7	26.87	13.43	0
1622:Manufacture of builders carpentry and joinery'	50	1	54	46	0	0
1623:Manufacture of wooden containers	3	1	66.67	33.33	0	0
170:Manufacture of paper and paper products	11	1	54.55	45.45	0	0
1701:Manufacture of pulp; paper and paperboard	352	1	50	43.75	6.25	0
1702:Manufacture of corrugated paper and paperboard and of containers of paper and paperboard	132	1	55.3	39.39	5.3	0
1811:Printing	11	1	54.55	0	45.45	0
1812:Service activities related to printing	5	1	60	40	0	0
19:Manufacture of coke and refined petroleum products	1	1	100	0	0	0
1910:Manufacture of coke oven products	9	1	55.56	0	44.44	0
1920:Manufacture of refined petroleum products	397	1	47.1	37.28	15.62	0
19a: Liquid and gaseous fuels from biomass	188	3	45.74	5.85	48.4	0
20:Manufacture of chemicals and chemical products	34	1	100	0	0	0

2011:Manufacture of basic chemicals	1596	1	63.66	30.14	6.2	0
2011a: Manufacture of nuclear fuels	205	3	34.15	6.83	59.02	0
2012:Manufacture of fertilizers and nitrogen compounds	77	1	55.84	38.96	5.19	0
2013:Manufacture of plastics and synthetic rubber in primary forms	679	1	54.49	44.33	1.18	0
2021:Manufacture of pesticides and other agrochemical products	172	1	63.95	36.05	0	0
2022:Manufacture of paints; varnishes and similar coatings; printing ink and mastics	46	1	67.39	32.61	0	0
2023:Manufacture of soap and detergents; cleaning and polishing preparations; perfumes and toilet preparations	89	1	58.43	41.57	0	0
2029:Manufacture of other chemical products n.e.c.	60	1	70	20	10	0
2030:Manufacture of man-made fibres	7	1	100	0	0	0
2219:Manufacture of other rubber products	9	1	55.56	0	44.44	0
2220:Manufacture of plastics products	108	1	59.26	30.56	10.19	0
2310:Manufacture of glass and glass products	148	1	58.78	22.97	18.24	0
239:Manufacture of non-metallic mineral products n.e.c.	7	1	57.14	0	42.86	0
2391:Manufacture of refractory products	20	1	60	10	30	0
2392:Manufacture of clay building materials	45	1	57.78	4.44	37.78	0
2394:Manufacture of cement; lime and plaster	311	1	40.51	20.9	38.59	0
2395:Manufacture of articles of concrete; cement and plaster	149	1	57.05	0	42.95	0
2396:Cutting; shaping and finishing of stone	9	1	66.67	0	33.33	0
2399:Manufacture of other non-metallic mineral products n.e.c.	178	1	62.36	15.73	21.91	0
2410:Manufacture of basic iron and steel	165	1	61.82	38.18	0	0
2420:Manufacture of basic precious and other non-ferrous metals	346	1	64.74	27.46	7.8	0
2420a: Smelting and refining of uranium	7	1	57.14	0	42.86	0
2432:Casting of non-ferrous metals	8	tied	50	0	50	0
25:Manufacture of fabricated metal products; except machinery and equipment	50	1	52	48	0	0
2511:Manufacture of structural metal products	38	1	55.26	44.74	0	0
2512:Manufacture of tanks; reservoirs and containers of metal	70	1	55.71	4.29	40	0
259:Manufacture of other fabricated metal products; metalworking service activities	15	1	66.67	33.33	0	0
2591:Forging; pressing; stamping and roll-forming of metal; powder metallurgy	117	1	66.67	33.33	0	0
2592:Treatment and coating of metals; machining	412	1	61.17	36.41	2.43	0
2610:Manufacture of electronic components and	437	1	78.95	12.59	8.47	0

boards						
2620:Manufacture of computers and peripheral equipment	82	1	100	0	0	0
2630:Manufacture of communication equipment	6	1	66.67	0	33.33	0
2651:Manufacture of measuring; testing; navigating and control equipment	27	1	81.48	18.52	0	0
27:Manufacture of electrical equipment	13	1	100	0	0	0
2710:Manufacture of electric motors; generators; transformers and electricity distribution and control apparatus	97	1	75.26	14.43	10.31	0
2710a: Manufacture of electric motors; generators; for liquid fuels	3	1	66.67	33.33	0	0
2720:Manufacture of batteries and accumulators	33	1	75.76	0	24.24	0
2732:Manufacture of other electronic and electric wires and cables	6	1	100	0	0	0
2790:Manufacture of other electrical equipment	98	1	60.2	24.49	15.31	0
2811:Manufacture of engines and turbines; except aircraft; vehicle and cycle engines	60	1	60	28.33	11.67	0
2811a: Manufacture of engines and turbines for liquid fuels; except aircraft; vehicle and cycle engines	3	1	66.67	33.33	0	0
2812:Manufacture of fluid power equipment	7	1	57.14	0	42.86	0
2813:Manufacture of other pumps; compressors; taps and valves	19	1	57.89	42.11	0	0
2815:Manufacture of ovens; furnaces and furnace burners	465	1	53.76	3.23	43.01	0
2815a: Manufacture of furnaces and boilers for liquid fuels	37	1	54.05	0	45.95	0
2815b: Manufacture of permanent mount non-electric household heating equipment	36	1	52.78	0	47.22	0
2816:Manufacture of lifting and handling equipment	9	1	55.56	44.44	0	0
2817:Manufacture of office machinery and equipment (except computers and peripheral equipment)	28	1	60.71	39.29	0	0
2818:Manufacture of power-driven hand tools	6	1	66.67	33.33	0	0
2819:Manufacture of other general-purpose machinery	247	1	58.3	22.27	19.43	0
2821:Manufacture of agricultural and forestry machinery	42	1	57.14	0	42.86	0
2822:Manufacture of metal-forming machinery and machine tools	45	1	66.67	33.33	0	0
2823:Manufacture of machinery for metallurgy	7	1	71.43	28.57	0	0
2824:Manufacture of machinery for mining; quarrying and construction	12	1	66.67	33.33	0	0
2829:Manufacture of other special-purpose ma-	13	1	61.54	38.46	0	0

chinery						
2910:Manufacture of motor vehicles	90	1	74.44	24.44	1.11	0
2930:Manufacture of parts and accessories for motor vehicles	22	1	59.09	31.82	9.09	0
3011:Building of ships and floating structures	26	1	69.23	30.77	0	0
3011a: Construction of drilling platforms	7	1	100	0	0	0
3020:Manufacture of railway locomotives and rolling stock	28	1	60.71	17.86	21.43	0
3030:Manufacture of air and spacecraft and related machinery	12	1	66.67	33.33	0	0
3091:Manufacture of motorcycles	19	1	73.68	26.32	0	0
3092:Manufacture of bicycles and invalid carriages	9	1	55.56	44.44	0	0
3314:Repair of electrical equipment	27	1	62.96	7.41	29.63	0
3315:Repair of transport equipment; except motor vehicles	56	1	57.14	14.29	28.57	0
35:Electricity; gas; steam and air conditioning supply	4	tied	50	50	0	0
3510:Electric power generation; transmission and distribution	2497	3	6.29	0.92	66.28	26.51
3510a: Electric power generation based on liquid fuels	480	3	5.21	1.46	62.71	30.63
3510b: Electric power generation; photovoltaic	540	3	13.33	1.11	66.67	18.89
3520:Manufacture of gas; distribution of gaseous fuels through mains	146	3	36.3	1.37	62.33	0
3530:Steam and air conditioning supply	626	3	27.32	8.15	50.16	14.38
3530a: Steam and air conditioning supply based on liquid fuels	56	1	37.5	26.79	35.71	0
3530b: Solar collectors	19	3	47.37	0	52.63	0
3600:Water collection; treatment and supply	27	1	48.15	33.33	18.52	0
3700:Sewerage	281	1	55.87	0	44.13	0
3811:Collection of non-hazardous waste	33	1	42.42	27.27	30.3	0
382:Waste treatment and disposal	5	1	100	0	0	0
3821:Treatment and disposal of non-hazardous waste	1286	3	45.96	0.23	50.39	3.42
3822:Treatment and disposal of hazardous waste	296	1	58.11	2.36	39.53	0
3830:Materials recovery	836	1	62.56	6.22	31.22	0
3900:Remediation activities and other waste management services	12	1	83.33	0	16.67	0
4100:Construction of buildings	432	1	53.7	3.24	43.06	0
4100a: Construction of factory buildings for the metal industry	71	1	59.15	26.76	14.08	0
4210:Construction of roads and railways	34	1	58.82	8.82	32.35	0
4220:Construction of utility projects	228	1	58.77	3.07	38.16	0
4220a: Construction of utility projects for electrici-	335	1	72.24	7.76	20	0

ty production; except for liquid fuels						
4220b: Construction of utility projects for electricity production; for liquid fuels	14	1	57.14	42.86	0	0
4290:Construction of other civil engineering projects	402	1	60.7	15.42	23.88	0
4290a: Construction of infrastructure for petroleum refining and distribution	18	1	55.56	44.44	0	0
4312:Site preparation	13	1	69.23	30.77	0	0
4321:Electrical installation	1	1	100	0	0	0
4322:Plumbing; heat and air-conditioning installation	291	1	51.55	0	48.45	0
4322a: Installation of solar collector systems	20	1	60	0	40	0
4390:Other specialized construction activities	29	2	31.03	58.62	10.34	0
4520:Maintenance and repair of motor vehicles	42	1	64.29	19.05	16.67	0
4540:Sale; maintenance and repair of motorcycles and related parts and accessories	26	1	65.38	0	34.62	0
4911:Passenger rail transport; interurban	10	3	20	0	80	0
4912:Freight rail transport	30	3	33.33	10	56.67	0
4921:Urban and suburban passenger land transport	11	1	63.64	0	36.36	0
4922:Other passenger land transport	290	1	55.17	41.03	3.79	0
4923:Freight transport by road	46	1	65.22	30.43	4.35	0
4930:Transport via pipeline	30	3	43.33	10	46.67	0
5012:Sea and coastal freight water transport	9	1	100	0	0	0
5022:Inland freight water transport	10	1	60	40	0	0
5110:Passenger air transport	9	1	77.78	22.22	0	0
5120:Freight air transport	5	1	60	40	0	0
6110:Wired telecommunications activities	15	1	60	0	40	0
68:Real estate activities	18	3	38.89	11.11	50	0
7110:Architectural and engineering activities and related technical consultancy	6	1	66.67	16.67	16.67	0
8219:Photocopying; document preparation and other specialized office support act	82	1	48.78	21.95	29.27	0
8292:Packaging activities	34	1	55.88	0	44.12	0
9529:Repair of other personal and household goods	7	1	57.14	0	42.86	0