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From oil wealth to green growth

An empirical agent-based model of recession, migration and sustainable urban transition

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Abstract
This paper develops an empirical, multi-layered and spatially-explicit agent-based model that explores sustainable pathways for Aberdeen City and surrounding area to transition from an oil-based economy to green growth. The model takes an integrated, complex system approach to urban systems and incorporates the interconnectedness between people, households, businesses, industries and neighbourhoods. We find that the oil price collapse could potentially lead to enduring regional decline and recession. With green growth, however, the crisis could be used as an opportunity to restructure the regional economy, reshape its neighbourhoods, and redefine its identity in the global economy. We find that the type of the green growth and the location of the new businesses will have profound ramifications for development outcomes, not only by directly creating businesses and employment opportunities in strategic areas, but also by redirecting households and service businesses to these areas. New residential and business centres emerge as a result of this process. Finally, we argue that industries, businesses and the labour market are essential components of a deeply integrated urban system. To understand urban transition, models should consider both household and industrial aspects.

Highlights

- An empirical, multi-layered and spatially-explicit agent-based model has been developed to study the complex process of urban transition
- An integrated, complex system approach has been used to model interconnected agents
- Spatial planning has important indirect ramifications in the long-run development of an urban area
- Industries, businesses and the labour market should be included in urban system modelling

Keywords: spatial agent-based model; recession, migration; urban transition; oil crises; sustainability

1 Introduction

Many cities emerge and become successful because of their unique geographic location (such as being a port) or proximity to natural resources (such as coal and oil). There is a strong path dependence in the development of a city based on its initial competitive advantage in the industrial structure. However, as technologies progress and industries move away from being location-dependent or resource-intensive, many industrial cities struggle to find a new niche in the global economy. The transition from a conventional resource-based economy to a knowledge-based one is not always a smooth path. Those that have failed to do so have suffered decades of decline and shrinkage (Audirac et al., 2012; Martinez-Fernandez et al., 2012).

Urban decline is a global phenomenon. It has happened in Europe, Japan, Australia and the United States (Martinez-Fernandez et al., 2016). It is a multidimensional process often featuring a fall in investment and job opportunities, followed by high unemployment rate, large-scale emigration and population loss (Fol, 2012). Rink et al. (2012) look at the long-term shrinkage of the former East Germany city of Leipzig, and of Liverpool in the UK, where populations shrank by 38.7% and 49.5% respectively between 1933 and 2001. Besides political and historic reasons, the authors associate the decline of the two cities to the massive loss of industrial jobs: Leipzig lost 85% of its industrial jobs within a few years after the reunification in 1989; Liverpool lost a third of all its employment between 1971 and 1985 due to the decline in factory and port-related jobs.

Worse still, the decline of the city often entails selective migration: the young, the rich and the qualified are the first to leave the city, leaving behind the old, the poor and the uneducated (Fol, 2012; Lang, 2000; Martinez-Fernandez et al., 2012). Martinez-Fernandez et al. (2012) and Martinez-Fernandez and Wu (2007) describe the disappearing knowledge, skills and innovation during urban decline: as people with skills and knowledge leave the city for job opportunities elsewhere, they also take with them the very assets the city would need to prosper in a knowledge and innovation-based economy. Moreover, because this process is gradual and silent, it tends to be overlooked until it is too late. Once the brain drain starts, it becomes increasingly difficult for the region to attract new businesses and skilled labour and to keep existing ones, both of which the region needs to recover from the decline. A vicious circle has been triggered.

Local people who lost their jobs during the industry decline can be stuck in long-term unemployment if they cannot be reemployed soon. Research shows that the probability of obtaining a job decreases the longer a person has been unemployed (Calvo-Armengol and Jackson, 2004), and that long term unemployment itself reduces a person's chance of leaving unemployment (Jackman and Layard, 1991). For example, in Britain in early 1984, only 4% of people who were unemployed for more than four years found a job in each quarter, compared with 40% of people who have only been unemployed for three months (Jackman and Layard, 1991). Data also suggest that a substantial number of long-term unemployed people become discouraged and cease to be active in job searching (Autor and Duggan, 2003; Katz, 2014). From a human resource point of view, workers accumulate skills on the job and lose skills during unemployment (Acemoglu, 1995; Lars Ljungqvist and Thomas J. Sargent, 1998). In other words, skills depreciate if not put to use (Edin and Gustavsson, 2008; Görlich and De Grip, 2008; Laureys, 2014). Thus the longer a person stays unemployed, the fewer marketable skills they have left. Structural changes in the economy also make it harder to adapt and acquire new skills the longer a person stays out of the job market (Katz, 2014; Layard, 1999). Finally, factors such as social exclusion (Kieselbach, 2003) and social norms (Andrew E. Clark, 2003) also contribute to the stickiness of long-term unemployment.

In urban land-use simulation modelling literature, the economic and employment aspects of a region are often treated as exogenous, if they are considered at all. Most regard urban outcomes as a result of households' residential choices, demographic type and preferences, and do not consider employment opportunities and economic growth as an integral part of urban dynamics (Brown et al., 2004; Caillault et al., 2013; Filatova et al., 2013; Gaube and Remesch, 2013; Haase et al., 2010; Jackson et al., 2008; Millington et al., 2009). For example, Haase et al. (2010) develop an agent-based model of residential mobility in the shrinking city of Leipzig, Germany, and treat economic and population growth as exogenous factors. Similarly, Gaube and Remesch (2013) develop an agent-based model of household residential decisions in Vienna, a city that has gone through negative population growth for decades until the 1990s. The authors consider the impact of urban planning and household demographic shifts, but not the industrial structure in the region.

The general economic literature, on the other hand, regards major shocks to a region's economy as mere disturbances that cause the region to deviate from its equilibrium growth path. It does not, however, explain why regions starting at similar conditions have very different development paths. Simmie and Martin (2010) compared the development paths of Cambridge and Swansea in the UK, and found that although the two regions had similar economic and employment conditions in 1970s and both had been through nation-wide economic recessions, they have led very different growth paths since then. By 2000, Cambridge had become one of the world's leading hubs for high-tech industry and innovation, whereas Swansea had suffered from permanent contraction in economic activity and employment. The authors argue that the development of a region is highly path-dependent: the pre-existing infrastructure, human resources, skills and connections enabled Cambridge to create growth opportunities, and thus has successfully upgraded and diversified its economy. Cities, they argue, are more like organic, self-regulated complex systems that are constantly evolving and adapting to a changing environment, than (quasi-)linear systems converging to equilibrium (Batty, 2007; Boschma, 2015; Jabareen, 2013; Simmie and Martin, 2010).

One of the founding stones of urban economics is the Alonso (1964), Muth (1969), Mills (1972) (AMM) framework, which formalizes the density and spatial distribution of population driven by transport cost, land price and wages. The original AMM framework is based on closed monocentric cities where all employment and production takes place in the Central Business District (CBD) and feature homogenous utility-maximizing agents, although recent extensions have modelled polycentric cities (Lemoy et al., 2017), heterogeneous agents (Olner et al., 2015) and open cities (Larson and Yezer, 2015). The AMM model assumes that the location of firms and services are fixed and regardless of households' residential choice; whereas in reality, firms tend to stay close to the market, especially those providing services to households. The AMM model achieves equilibrium when no agent in the model has an incentive to relocate; whereas in real life, as people go through different stages of life, their preferences will change, so will their optimal residence. The static equilibrium will not last if we take a dynamic approach and allow people to grow in life. Urban dynamics can then be influenced by gradual demographic shifts in the population. Finally, in the AMM framework, households' residential choice is highly simplified and based only on transport cost, space, wage and housing price. They do not consider other aspects such as neighbourhood and school quality, the quality and type of the house itself and their availability. The model presented in this paper will address these issues not considered in the AMM framework.

The paper conducts a case study of Aberdeen City and Shire in Northeast Scotland, UK; home to more than 400,000 people. The economy of Aberdeen has been heavily reliant on the North Sea oil and gas industry since the 1970s. Thanks to the oil wealth, for decades prior to the collapse in oil price in late 2014, Aberdeen had seen rapid economic and population growth and a swell of prosperity, and still has among the highest income per capita and lowest unemployment rate in the UK. However, since the oil price collapse, the local economy has been in turmoil with significant job losses and pay cuts in the oil and gas sector. The loss of customers, businesses and financial supporters from the oil industry also affects other local businesses. Moreover, reduction in tax income affects the council's ability to provide public services when it is most needed: the number of people that applied for unemployment benefits surged after the oil price collapse (Ambrose, 2016). Now, almost three years later, there are few signs of recovery.

Meanwhile, people start to question the dominant role of North Sea oil and gas in Aberdeen's economy and the future of the city (Davies, 2017). Research shows that cities relying heavily on a single sector are especially susceptible to economic shocks (Lang, 2005). The solution, many argue, is to develop a green industry that could make use of the existing knowledge and expertise in the energy sector. In fact, both Aberdeen City and Shire councils already have plans to promote green energy businesses that could be built on the region's rich oil and gas heritage, such as carbon capture and storage technology, hydrogen, onshore and offshore renewable energy. The recent oil crisis could just be the push needed (Vaughan, 2017), although to convert existing knowledge and resources into new competences is not always straightforward (Maskell and Malmberg, 2007). Once again, Aberdeen is at the critical point of change many cities have faced before: should it successfully upgrade its industrial structure after the crisis, it will become a stronger and more resilient region. If not, the once prosperous city may fall into a long-term decline. The stakes are high.

The GLAMURS[1] (Green Lifestyles, Alternative Models and Upscaling Regional Sustainability) project was funded by the European Commission's Seventh Framework Programme to research alternative ways of life that are more environmentally sustainable, and investigate the scope for upscaling them to the regional level. The decline of the oil industry in the Aberdeen area provides a backdrop against which to explore opportunities for regional restructuring leading to more sustainable ways of living in the area. Life stage transitions are critical opportunities for intervention, as people are developing new habits. The context of wider regional transition makes this case study particularly interesting. The project included a regional questionnaire survey of the area's inhabitants, and another survey of workers in the local municipality.

This paper develops a multi-layered, spatially-explicit agent-based model that includes the dynamic interactions between people, households, businesses, industries and neighbourhoods to study the impact of oil collapse and industrial restructuring on a city previously dominated by the oil industry. We will simulate and evaluate different transitional paths to potentially a more diverse, resilient and sustainable economy. We will examine factors such as the adaptability of the local labour force, the abundance of housing supply, the convertibility of knowledge between industries, the resilience and the adaptability of local businesses and workforce on the outcome of the transition. By modelling multiple layered and interconnected systems in the city, we are able to simulate the ramifications of various transition paths of an industrial urban area.

2 The agent-based model of lifestyles in a complex urban system

2.1 Model overview

We develop an empirical, spatially-explicit agent-based model of the residents, households, and businesses in Aberdeen. The model takes a holistic approach to look at major aspects of life, including education, career and jobs, income, family life, and residential choice and preferences, and we define lifestyle as the aggregation of these major life choices and events. The model is developed in Repast Simphony, a java-based open source simulation platform (North et al., 2013). In this

[1] See http://glamurs.eu/ for more information about the project

section, we will give an overview of the main structure and salient points of the agent-based model. A more detailed model description following the Overview, Design concepts, and Details protocol (Grimm et al., 2006; Grimm et al., 2010) can be found in the Appendix.

Central to the model's ontology are agents representing people. The Person class in the model is used to represent an individual person. During a person's life time, he or she may go through various life stages (child, married, divorced, etc.), as illustrated in Figure 1, as well as employment status (student, employed, unemployed, retired, etc.), as illustrated in Figure 2. The model is open. Every period new people are born into the model while old people die; newcomers may also enter the area as a student or employer or leave it for study or employment elsewhere. A Person may also belong to Households and may work for and receive services from Businesses.

Households are aggregations of Persons; the UML class diagram in Figure 4 shows their data and methods. Their attributes are initialized from regional survey data collected in the GLAMURS data. There are processes associated with the formation and evolution of Households associated with processes such as getting married, divorced, or leaving home. However, it is the Household that moves from one House to another, and the evolving preferences of the Household as they change job and life stage affects their residential choice and incentive to move. Houses have location and various attributes that influence Households' preferences for them, as shown in Figure 4, and are aggregated at the Neighbourhood level. The Neighbourhood's attributes, initialized from Scottish Index of Multiple Deprivation data, also influence Households' residential choice preferences, and are dynamically updated by processes that aggregate what is happening to the Businesses and Households in them.

Households' residential choice and behavioural mode are based on their budget, job location, household types, social, economic status and demographic characteristics, which is in line with the existing literature. For example, Haase et al. (2010) demonstrate the importance of household types and life cycles as the key determinants in the agent-based model of household residential choice. Crooks (2006) looks at the location of employment centres, travel cost and space requirement. Huang et al. (2014) conduct an extensive review on urban residential choice models used in agent-based models and identify a few key determinants of residential choices commonly included in the literature, including life-cycle events and daily activities (including travel to work), social, economic and demographic attributes, heterogeneous budget, preference, and risk attitudes, as well as the impact of the geographic location, environment and neighbourhoods. Finally, the behavioural rules adopted in the study has gone through a "health check" by the GLAMURS consortium of modellers, psychologists, sociologists and economists (Dimitru et al., 2016).

Businesses have a location, and provide employment and services. Services are provided to Persons and Households. Their methods are associated with hiring and firing employees, and if the Business is service-based, adjusting their growth rate according to local market and competition, and its location to be closer to the market it serves. Some Businesses, such as those in the oil industry and agriculture, do not provide services to the local market in this sense and thus do not relocate. Businesses are aggregated into Industries.

There are seventeen Industries, initiated from data from the Regional Skills Assessment Report and the Office for National Statistics (see 2.2.4 for more details). Some Industries require skilled labour, whilst others do not. In the model, a requirement for skilled labour means Businesses in that

Industry only recruits Persons with at least three years of training or equivalent experience. Businesses adjust the wages of their employees according to the income distribution for the Industry, the experience of the Person; the income distribution of the Industry is adjusted according to economic conditions and scenarios. Table 1 shows the full list of Industries. In some scenarios, an eighteenth Industry is added representing green industry.

People, Households and Businesses locate and interact in a common environment made up of Neighbourhoods. A neighbourhood is a small-area that contains households with similar social characteristics that shares facilities such as public school, hospitals, community centres, shop and other service providing entities. Neighbourhoods are heterogeneous in multiple dimensions, including the business/employment opportunities it offers, the quality of public school and hospital, convenience and accessibility, housing availability/affordability and so on. The Neighbourhood qualities are also endogenous in that they depend on the Households and Persons who live there, which is endogenous and dynamic. When deciding on residential location, Households evaluate multiple Neighbourhoods as well as the attributes of individual Houses, according to their heterogeneous needs, preferences and priorities. The heterogeneous, endogenous and multi-dimensional neighbourhood enables us to simulate the emergent neighbourhood characteristics and the evolving spatial dynamics over time.

The main data and methods associated with the agent classes are shown in the unified modelling language (UML) class diagram in Figure 4. Each period in the simulation represents a month in real time. In each period, people, households, business, industries and neighbourhoods update their statuses and feed into each other updated information. Figure 5 shows the order of execution of the various methods shown in the UML diagram in Figure 4, grouped by the agent class in which the methods are situated. Each cycle through these methods represents one month.

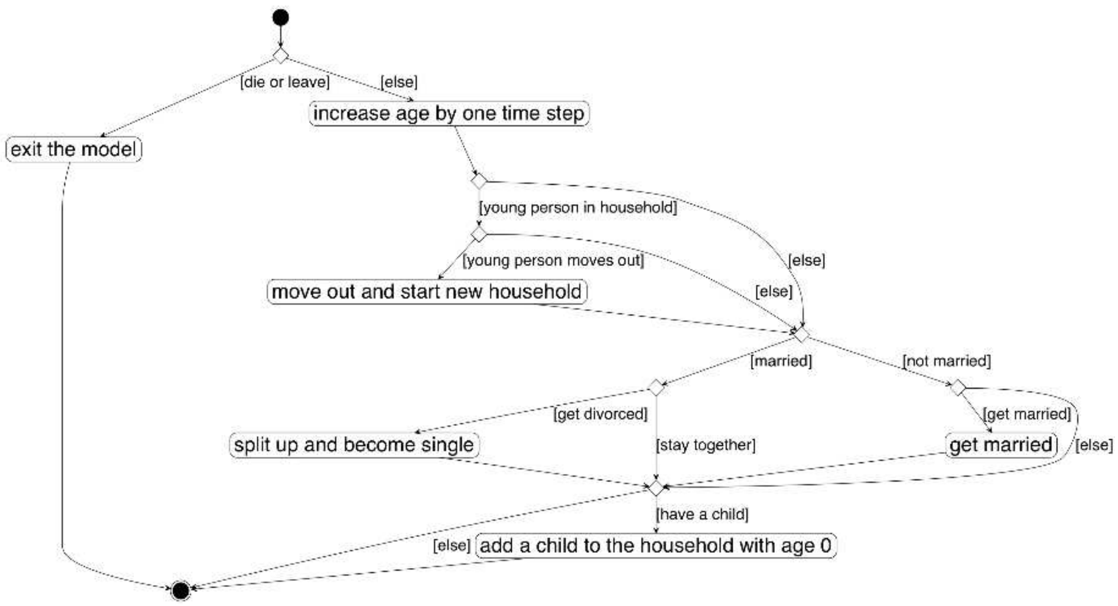

Figure 1 UML activity diagram showing the procedures leading to changes in a person's private life

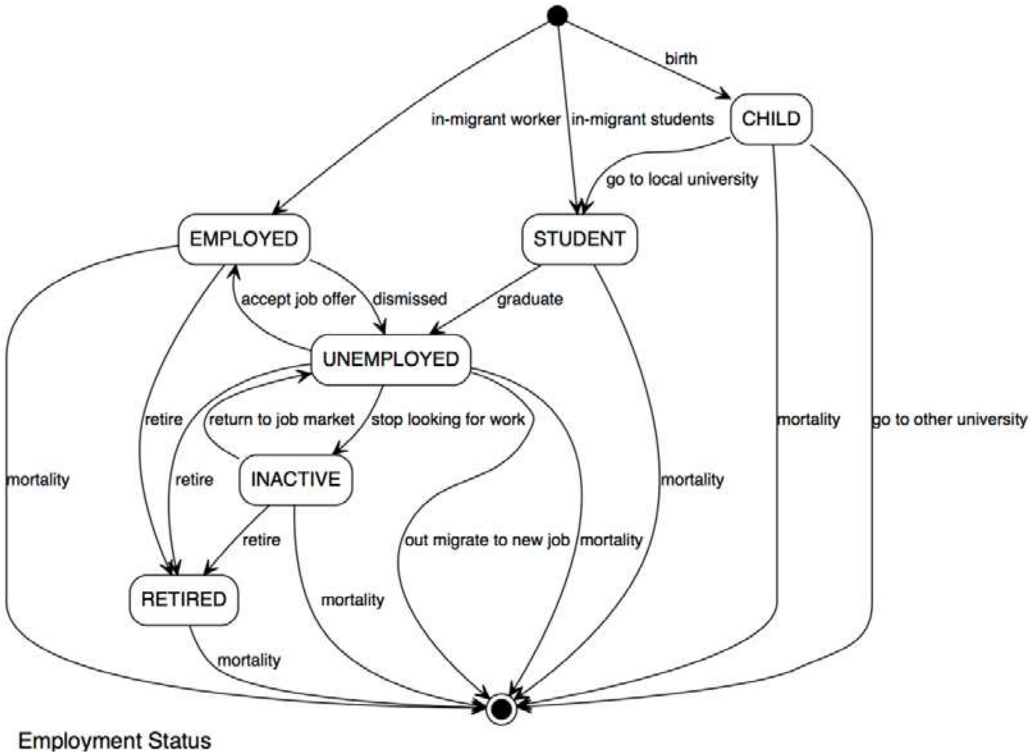

Figure 2 UML state chart diagram showing employment status update of Persons

Figure 3 Neighbourhood evolution through the interactions between people, households and businesses

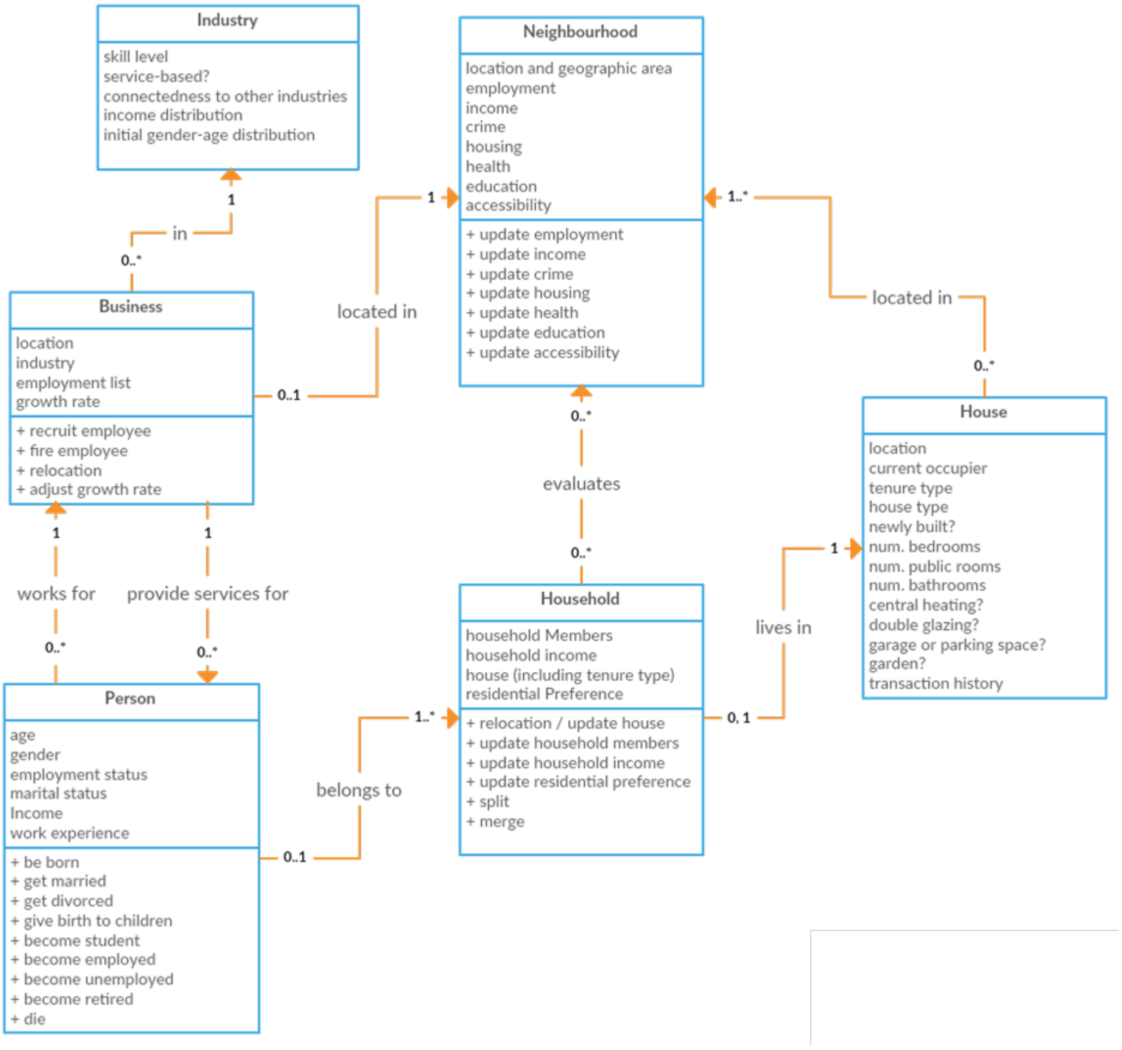

Figure 4 Simplified UML class diagram of DIReC

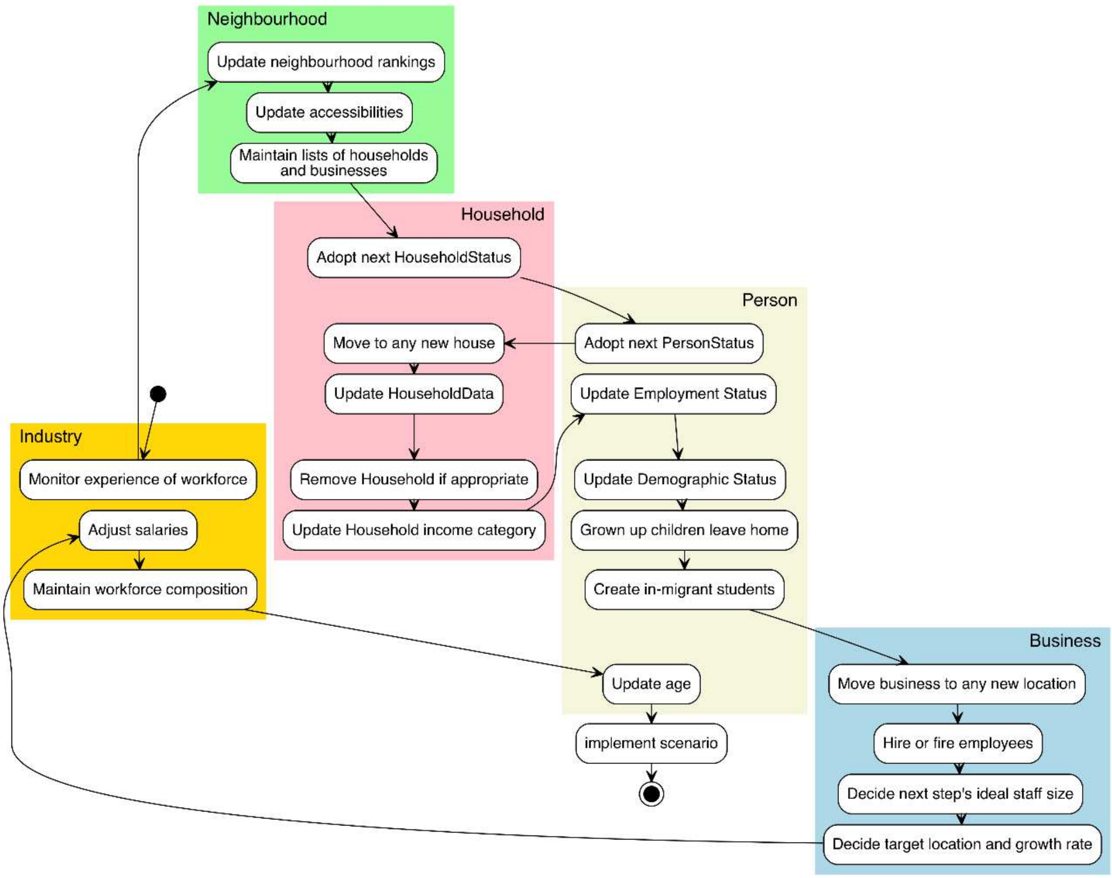

Figure 5 Simplified UML activity diagram

2.2 Data, initialization and model input

We have integrated multiple large-scale micro data[2] to use both for model initialization and model input, which we will discuss in this section.

2.2.1 Housing transaction data

The housing data including sale and rental transaction are from Aberdeen Solicitors Property Centre (ASPC). We use the housing data to initialize all the houses in the model, including the location, house types, house attributes, tenure type, and transaction history. The ASPC data covers most sales transactions and the majority of rental transactions in Aberdeen City and Shire since 1984 (a small percentage of informal rental transactions do not go through ASPC). Because the earlier transaction records do not have accurate postcode address needed to locate the house, we use only transaction records between January 1996 and March 2015. These data include more than 220,000 transactions, of which more than 90% are sales transactions, and the rest are rental transactions. It allows us to identify more than 80,000 unique properties in the area. The house attributes available in the data correspond to those of a house class listed in Table 5 in the appendix.

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[2] Ruggles, S., 2014. Big microdata for population research. Demography 51, 287-297. defines large-scale microdata as “Individual-level data on population such as census data, usually consist of high-density samples or complete census enumerations”.

2.2.2 Household survey data

In December 2015, we sent a postal survey to 10,000 randomly sampled households in Aberdeen City and Shire. The survey includes questions on the households' family members, their demographics such as age, gender and marital status, employment status, income, living situation and the households' residential preferences. More than 900 surveys were returned. After removing incomplete records, 748 sampled households were included in the model's database. More information regarding the sampling methodology and procedure and summary statistics of the sample can be found in Dimitru et al. (2016)(p. 187) and Craig et al. (2016)(p. 37).

In addition to the standard demographic information such as annual household income and employment status, the respondents are asked to specify each family member in the household, including their age, gender and the relationship to the respondent. We then use the information to generate a synthetic household population for the simulation. For example, if the household in the survey is made up of a middle-aged couple (one employed, one inactive), a teenage child and a grandmother (retired), we will create a counterpart household in the model that also has a middle-aged couple (one employed, one inactive), a teenage child and a retired grandmother. In other words, we use households from the survey as the "reference households" from which we simulate a synthetic population of households in the model. By Monte-Carlo sampling (random sampling with replacement) from the 748 reference households in the survey, we have created more than 5,000 matching households and more than 10,000 people during model initialization.

For each household in the sample, the survey asks the household to evaluate the importance of the following aspects when they move house in the near future, including 1) house price, 2) energy efficiency of the house, 3) safety of neighbourhood, 4) quality of parks / greenspace, 5) quality of schools, 6) distance to work, 7) good public transport, 8) availability of shops / cafes / supermarkets / restaurants, 9) access to healthcare services and 10) dwelling size. Each importance ranges from "not at all important" to "extremely important", and they are used to assign heterogeneous weights to the elements in the evaluation of residences. Items that are considered important by the respondent are assigned more weight, and vice versa. These aspects are consistent with the multi-dimensional household residential preferences (discussed in more detail in the Appendix, section A.1.2). The simulated households will have the same preferences and priority as their reference. We then use the priority to assign weights to the domain scores in the evaluation of neighbourhoods.

Finally, the survey asks about the household's current housing situation, including the type of the dwelling (flat, detached, etc.), the tenure type (rented, owned with mortgage, owned outright, social housing) and the characteristics of the accommodation (number of bedrooms, bathrooms, public rooms, whether it has a garage, and whether it has a garden etc.). We use the information to assign Houses to the Household agents as their current dwellings in the initialization.

2.2.3 Demographic data

Most demographic data are from Scottish Census data in 2011, including conditional distribution of employment, mortality rate, marriage and divorce rate. Mortality rate is defined by the probability that a person will die in a given period (a month here) given the person's age and gender. Similarly, marriage/divorce rate is the probability that a person will get married/divorced in a given period given the person's current marital status, age and gender. The employment data specify the number of people aged 16 and over in Aberdeen City and Shire in each gender-age group who are: part-time employee, full-time employee, self-employed, unemployed, retired, student, looking after home of family, and long-term sick or disabled. We group the first three categories as being employed, and the last two categories as being inactive. The gender-age groups by which the employment information is given are: males/females aged 16 to 34, 35-54, 55-74, and 75 and over. We use the employment statistics to initialize the employment status of people in the model.

The census data also provides information on the living arrangements of people. For each gender-age group, it gives the number of people who are married (or co-habiting with a partner). We then derive the probability that a single Person agent will get married in each period given the Person's gender and age, assuming a fixed annual divorce rate among married or co-habiting couples.

2.2.4 Industry data

The initial 17 industries are identified using industrial and business data from Office for National Statistics (ONS), including dataset entitled "Earnings by industry", "Earnings and working hours", "official labour market statistics: Labour Market Profile - Aberdeen City and Aberdeenshire", and the Regional Skills Assessment (Assessment, 2014) published by Aberdeen City and Shire. We also derive the size of employment in each industry as a percentage of total employment. Later on in the green growth scenarios, an 18th industry, the green industry, will be added. As expected, the oil and gas industry is the biggest industry in the region and currently employs almost 20% of the labour force. Together with supporting industries (e.g. the engineering and recruitment companies whose clients are oil and gas companies), oil-related industries currently employ almost 30% of the local labour force.

We assign the skill level to each industry according to expert knowledge and judgement to reflect the level of skill requirement (see Table 1). Although some jobs in an unskilled industry can be highly specialized, and vice versa, we believe that to a large degree it represents the overall skill requirement in the industry. Industries can also be service or non-service, depending on whether the industry serves local households directly. Service industries include public administration, human health, education, facilities (such as retail and catering), social services and so on. Non-service industries do not serve local households directly, including oil and gas, business to business services, agriculture, and manufacturing. As discussed earlier, service industries rely on the target market in the nearby neighbourhoods, and may decide to relocate to be close to it. Non-service businesses, on the other hand, will not relocate. The target market of service businesses depends on the type of services it provides (see Table 1). Most service businesses will serve local households and employees, but some will serve a certain demographic group. For example, non-tertiary education entities serve school age children only.

Since wage level can vary greatly across industries, we used the wage distribution statistics in each industry from ONS industrial and business data to initialize wage level in businesses in each industry. The data provides information on wage distribution at each decile (from 10% to 90%). The data shows that wage levels indeed differ hugely across industries. For example, the median (gross) weekly income is estimated to be £1023 in the oil and gas industry, but only £268 in the accommodation and tourism industry.

The gender and age distribution can also vary across industries. We use the gender-age joint distribution from the ONS industrial and business data to represent the population working in each industry, which provides information on the percentage of employees in each gender-age group for male and female and from 16 to 74. The data show that the gender and age compositions of employees indeed differ across industries. For example, the percentage of male employees is over 77% in the oil and gas industry and around 41% in accommodation and tourism. Regarding age, the percentage of employees under 40 years old is 44.3% in the oil and gas industry, and 64.3% in accommodation and tourism. We use the gender-age distribution to initialize the working population. During the simulation, when people choose their training in a university, their choices will reflect the current gender distribution of the industries, which could change over the course of the simulation. Table 1 lists the 17 industries in Aberdeen City and Shire, their employment percentage, whether each is skilled and whether it is service-based.

Table 1 Industries in Aberdeen

Industry	Initial %	Skilled?	Service? (Target market)
1. Oil and gas	19.8	Yes	No
2. Public administration	5	No	No
3. Human health	6.8	Yes	Yes (local households)
4. Tertiary education and research	2.3	Yes	No
5. Non-tertiary education	5.4	No	Yes (local school-age children)
6. Business to customer services (e.g. retail centre, shops)	5.8	No	Yes (local households & employees)
7. Business to business services – oil (e.g. recruiting, machine repair)	9.5	Yes	No
8. Business to business services – General (e.g. office supply)	5.7	No	No
9. Agriculture, manufacturing	9.5	No	No
10. Social services (e.g. church, community centre)	1.1	No	Yes (local households & employees)
11. Facilities (e.g. restaurants, pubs, supermarkets, post offices)	10.4	No	Yes (local households & employees)
12. Transportation	4.7	No	No
13. Arts, entertainment and recreation	1.8	No	Yes (local households & employees)
14. Construction	6.2	No	No
15. Real estate activities	1.3	No	Yes (local households & employees)
16. Residential care activities (e.g. nursing homes)	2.3	No	Yes (local households & employees)
17. Accommodation and tourism	2.4	No	No
18. Green	0	Yes	No

2.2.5 Geographic data

The Scottish Government has defined 6976 data zones in Scotland, which is the key small-area statistical geography in Scotland. Each data zone has between 500 to 1000 households and is considered to be a "common, stable and consistent" small-area that contains households with similar social characteristics (SIMD, 2016). In 2011, the Scottish government evaluated all data zones in the seven domains of employment, income, crime, housing, health, education and accessibility. An overall Scottish Index of Multiple Deprivation score (SIMD)[3] is derived from scores in all domains for each data zone to reflect the level of deprivation in the area.

[3] Scottish Index of Multiple Deprivation 2016 http://simd.scot/2016/#/simd2016/BTTTTTT/12/-2.1990/57.1510/

In the model we use data zones to represent Neighbourhoods. Each data zone has an overall score that represent its level of development or, conversely, deprivation, as well as individual scores in the seven domains (employment, income, crime, housing, health, education and accessibility). In 2011, 623 data zones have been identified in Aberdeen City and Shire. The model includes all geographic areas in Aberdeen City and Shire, although for the sake of visual clarity, in the Results section we will only present spatial results for the areas where businesses and households are more concentrated (see Figure 6).

We use seven-digit postcode to locate individual houses and businesses in the region. For individual businesses, we use address data from Ordnance Survey[4] that locates residential, business and public postal address to identify their industry and geographic location. We identify the type of the business from local knowledge and the name of the businesses. For large businesses, of which many are large international oil and gas companies, we consult the list of main employers from the council (Aberdeen City Council, 2015). For small businesses, we use keywords in their business name to identify their industry. There are a few dozen keywords that we use to identify businesses and the industry they belong to, including “café”, “school”, “post office”, “shop”, “bookmaker” as well as names of businesses such as “Tesco” that are part of national chains. Although not comprehensive, we believe we have identified a significant proportion of local businesses. In total, we have identified 6273 businesses, for which we know their geographic location and the industry to which they belong. Figure 6 shows the spatial distribution of houses, businesses and neighbourhoods in Aberdeen City and Shire. To enhance visual clarity, we will only present spatial results of the central areas in the Results section later. The simulation model, however, includes the entire region of Aberdeen City and Shire.

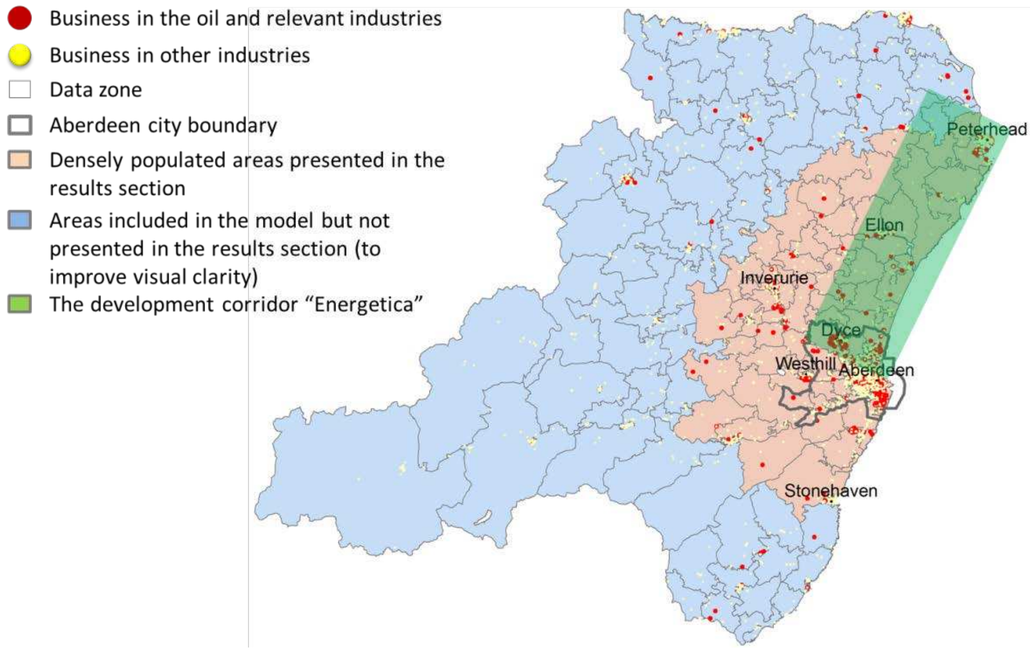

Figure 6 Businesses, neighbourhoods and development corridor in Aberdeen City and Shire[5]

[4] https://www.ordnancesurvey.co.uk/business-and-government/products/address-point.html

[5] Data from Ordnance Survey and Scottish Index of Multiple Deprivation 2016. More information on Energetica can be found in Section 2.3 and http://energetica.uk.com/about/what-is-energetica

2.3 Calibration and validation

Validation was a two-fold process. As Polhill and Salt (2017) discuss, in agent-based models, there is more to validation than fit-to-data: the model's structure (i.e. classes and methods, as in Figure 4 and Figure 5) is also important. Quantitative methods for assessing what is more appropriately termed *ontological interoperability* are not yet standardized, but Polhill and Salt (2017, p. 154) outline four main approaches: logical consistency, populating the ontology with instances, stakeholder/expert evaluation, and more general comparison of the ontology with other ontologies. A degree of logical consistency is of course implied by the successful compilation of the model, though obviously this is a relatively weak criterion. The model's structure is populated with instances during initialization: Person data from Scottish Census and ONS, Household data from the GLAMURS regional survey, House data from the ASPC house transaction data, Neighbourhood data from the SIMD 2016, Business data from OS, and Industry from ONS and Regional Skills Assessment. The successful initialization is thus also a validation of the model's ontology. The model was also constructed as part of the GLAMURS project, and its ontology presented and discussed with colleagues in the project team as the project progressed. The interdisciplinary team included economists, sociologists, industrial ecologists, psychologists and econometricians. A modelling 'health check' exercise, documented in Dimitru et al. (2016) included this model as one of the models evaluated (p. 81-106).

The model's macro-level outputs were qualitatively validated to ensure that its behaviour was as expected (stabilization) without external scenario stimulus. Specifically, the evaluation confirmed that there was close to zero net migration regionally and among neighbourhoods, and no significant change in population density, demographics, number of households, distribution of household size, distribution of income and employment, or neighbourhood quality. Since the model is open and dynamic, there is no direct control over these macro-level outcomes without adjusting the micro procedures that influence them. Grimm et al. (2005) introduce the idea of pattern-oriented modelling where agent-based models of complex systems are developed and validated by the matching of multiple patterns simultaneously. In a similar way, we are able to show that, without imposing direct control, the complex system can operate itself in a balanced and sensible way on multiple output dimensions simultaneously. Achieving these outcomes is therefore not as trivial as it might appear at face value, and is consistent with Epstein (2006)'s soundbite for generative social science: "If you didn't grow it, you didn't explain it." (p. xii).

3 Scenarios

To illustrate the model, we compare four scenarios regarding the future of the oil and gas industry and the city's transition to a green economy. The first scenario is the "No oil price collapse", where no collapse or major change takes place. To a certain extent, it can be considered the best case scenario where the oil industry remains intact and no disruption occurs to the local economy. The second scenario is "Oil price collapse and no green growth", which involves the collapse of oil prices and the consequent pay cut and job losses in the oil and gas industry. The collapse lasts 24 periods (two years in real time), during which employment size and wages shrink in the oil industry. Employment and wages then stabilize and stay at a low level after the two-year collapse period.

The third and fourth scenarios are "oil collapse and green growth – low/high value" respectively. Both scenarios involve the collapse of the oil industries and the growth of the newly created green industry. The differences between the two lie in the growth rate, the initial wage level in the green industry, and the level of knowledge transfer from the oil to the green industry. In the high value green growth scenario, the green industry is closely related to the oil and gas sector (off-shore wind energy or other renewable energy, for example), so that it can better take advantage of the existing expertise and infrastructure in the oil and gas industry. Maskell (2001) discusses the advantage of having related industries co-located in an area so that the industries benefit from an enhanced ability to create knowledge by variation and a deepened labour division. In this case, the green industry in Aberdeen can benefit from the knowledge and connections of former oil employees, as well as the existing infrastructure and established supply chain in the energy sector. Therefore, it can enjoy a competitive edge over other regions, and provide higher wages to its employees.

The low value green growth, on the other hand, is unrelated to the oil and gas industry (organic farming, for example). It is built from scratch and does not necessarily use the existing industrial expertise and infrastructure. As a result, it can only afford much lower wage level at the beginning. Although with both green growth scenarios, the size and wage level of the green businesses will grow as time goes on. Both green growths last 60 periods (5 years in real time), during which the size and wage level in the green industries grow steadily and remain at the same level as at the end of the growth period afterwards.

Table 2 Scenarios

Scenario	Oil size *g*[1] (duration[2])	Oil wage *g* (duration)	Green size *g* (duration)	Green wage *g* (duration)	Green starting wage	Green recruit difficulties	Knowledge conversion between oil and green
1. No oil price collapse	0%	0%	N/A	N/A	N/A	N/A	N/A
2. Oil price collapse and no green growth	-5% (24)	-2.5% (24)	N/A	N/A	N/A	N/A	N/A
3. Oil price collapse and low-value green growth	-5% (24)	-2.5% (24)	1% (60)	2% (60)	low	high	low
4. Oil price collapse and high-value green growth	-5% (24)	-2.5% (24)	1% (60)	2% (60)	high	low	high

[1] monthly growth rate [2] in months

Another strategic decision is where to encourage the green businesses to locate. The location decision could have a profound impact in the region and provide opportunities to develop and reshape the neighbourhoods. In fact, Aberdeen City and Shire councils have worked together to establish a development corridor called "Energetica" (Figure 6), which aims to attract energy, engineering and technology firms with access to local expertise in the energy industry and an already established supply chain (Energetica, 2015). The councils hope that Energetica will become a centre for innovation and growth in renewable energy. It offers a range of financial incentives and assistance schemes to help business relocate there, as well supporting facilities such as housing and transport. In the model the new green business will be located in Energetica.

4 Results

We run the simulation for 300 periods, with each period representing a month in real time. We exclude the first 60 periods as burnout, and show the time series results for the remaining 240 periods (20 years), during which the oil collapse and green growth occur if the model is so configured. Throughout the section, we will use a red rectangle to represent the oil collapse period (starting at period 6 and last for 24 periods), and a green rectangle to represent the green growth period (starting at period 12 and last for 120 periods). There is an overlap between the oil collapse and green growth.

Figure 7 shows the number of people of different age groups under the four scenarios. Under the no oil collapse scenario, the numbers of incoming and exiting people in each period are roughly in balance. Therefore, the total population as well as the number of people of all ages remains stable over the course of the simulation. Under oil collapse scenario, the number of people goes down quickly when the oil collapse happens, and stabilizes afterwards. Under both green growth scenarios, the number of people drops at first when oil collapse happens, and gradually recovers over time after green growth starts. Under the low value growth, the change in total population is more pronounced than that under high value growth, because the latter can more quickly absorb and reemploy former oil workers that in the green industry, thus reducing the need to bring in new workers from outside.

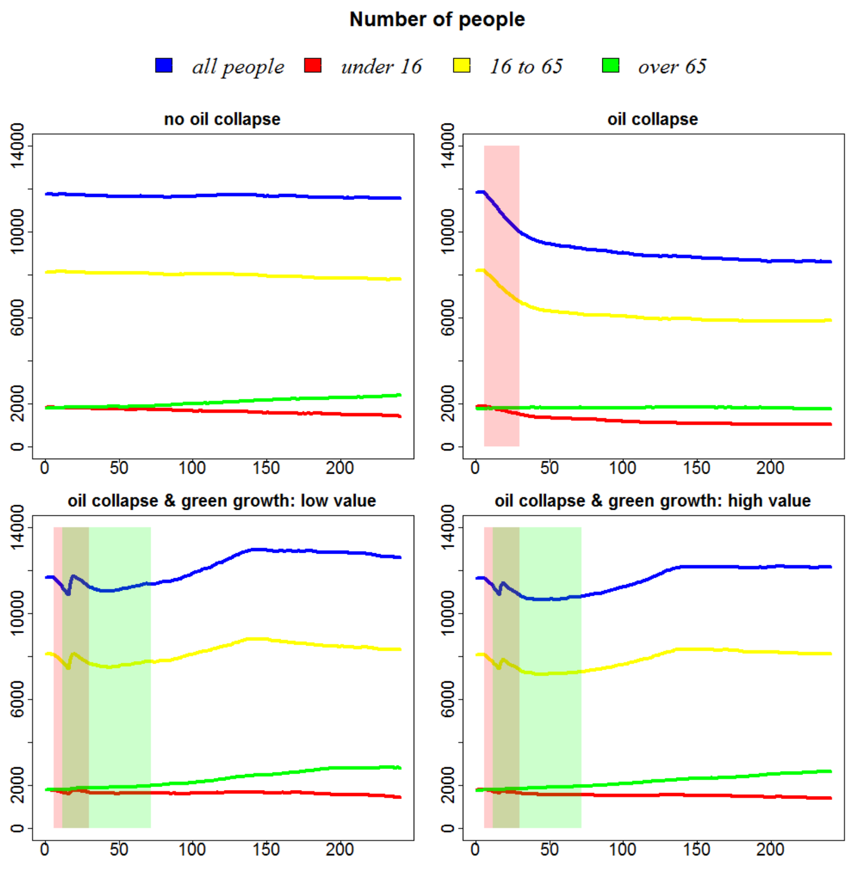

Figure 7 The number of people of different age groups under the four scenarios

Figure 8 shows the number of households of different income groups under the four scenarios. Under the no oil collapse scenario, the number of total households remains relatively stable over the course of the simulation, and so are the numbers of low, medium and high income household. We see that low income households are largest in number, followed by medium income ones, followed by high income ones. Under the oil collapse scenario, the total number of households drops as some former oil workers relocate. The number of low income households surges, whereas the number of high income households plunges. Without green growth, the number of high income households never recovers to its pre-collapse level.

With green growth, on the other hand, the numbers of medium and high income households does recover and, depending on the type of growth, may even exceed their pre-collapse level. Under low value green growth, since the wage in the green industry is lower (though it grows over time), the number of medium income households increases gradually and exceeds its pre-collapse level at the end of the period, but not the number of high income households. Under high value green growth that offers a higher starting wage, the number of high income households grows significantly during the green growth period and exceeds its pre-collapse level and even the number of medium income households.

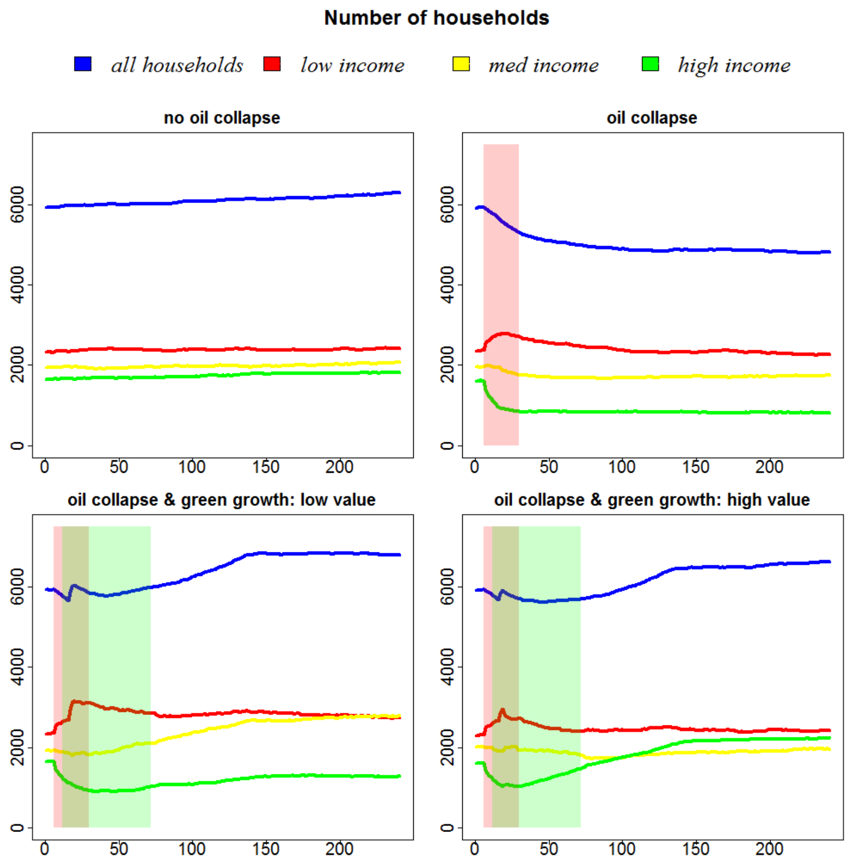

Figure 8 The number of households of different income groups under the four scenarios

Figure 9 shows the unemployment and inactive rate under the four scenarios. The moment oil price collapses, the unemployment rocketed as oil workers are laid off. Inactive rate also increases over time after the oil collapse because some unemployed workers may give up looking for a job during the process. Under the oil collapse scenario, the unemployment and inactive are still noticeably higher than its pre-collapse level 20 years after oil collapse happened.

In both green growth scenarios, unemployment rate starts to fall once the green industry starts to take off. The difference between the low and high value green growth is how fast it falls: under low value growth, the unemployment rate falls slowly and gradually after oil collapse; while under high value growth, it falls sharply, and the unemployment rate returns to its pre-collapse level shortly after the oil collapse. This difference explains why, at the end of the 20-year period, the inactive rate in the low growth scenario is much higher than that in the high growth scenario. As previously discussed, the longer a person stays unemployed, the more likely that the person becomes inactive (Calvo-Armengol and Jackson, 2004). Once a person becomes inactive, he/she will no longer make use of any job opportunities, even if the skills and experience of the person is much needed in the market, unless the person decides to be active again. Therefore, the quicker the job market recovers, the fewer these missed opportunities are and the less waste of human resources.

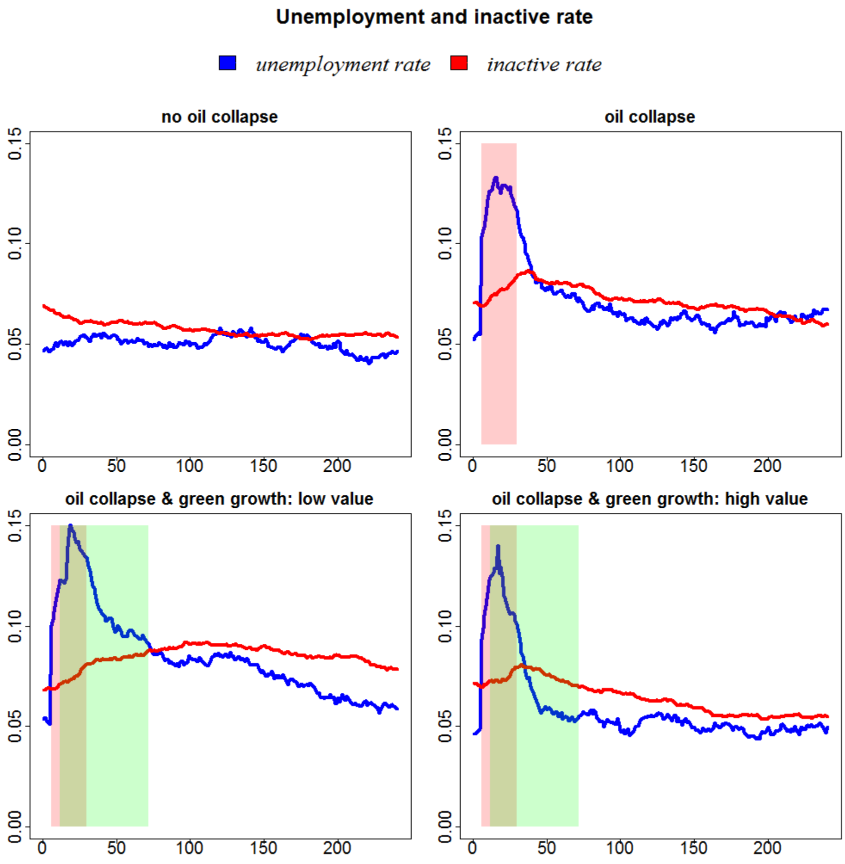

Figure 9 Unemployment and inactive rate under the four scenarios

We now compare the spatial distribution of population, jobs, services etc. under different scenarios at the end the simulation of year 20, or equivalently, period 300 (60 burnout periods plus 240 subsequent periods). For the purpose of visual clarity, we only show results in the more densely populated areas, including Aberdeen city and the suburbs and the development corridor, Energetica, while the simulation covers the entire region of Aberdeen City and Shire. We rank the data zones or neighbourhoods across all scenarios by the attribute of concern, and colour coded them according to the decile (10%, 20% … 100%) of their rankings (a similar visualization approach used in The Scottish Index of Multiple Deprivation).

Figure 10 shows the distribution of jobs or employment opportunities across Aberdeen City and the surrounding areas. We see that under the no collapse scenario, most jobs are located in Aberdeen city centre. There are few jobs centre outside of Aberdeen city, and the further away it is from the centre, the fewer jobs are available. Under the oil collapse scenario, the CBD in Aberdeen city centre has shrunk considerably due to the massive job losses in the oil sector and the consequent job losses in the service sector due to decrease in demand.

With green growth, the employment opportunities are more or less recovered in the city centre. Moreover, new employment centres have emerged in the development corridor of Energetica, where the green industry is located. In addition to the green industry, service businesses may also relocate to those areas to meet the growing needs of the businesses and households there. At the same time, the Aberdeen city has shrunk slightly in size, which may be desirable as it could alleviate congestion and over-crowding in the city centre. Overall, having a more balanced spatial distribution of employment opportunities could benefit both the city centre and the neighbouring towns.

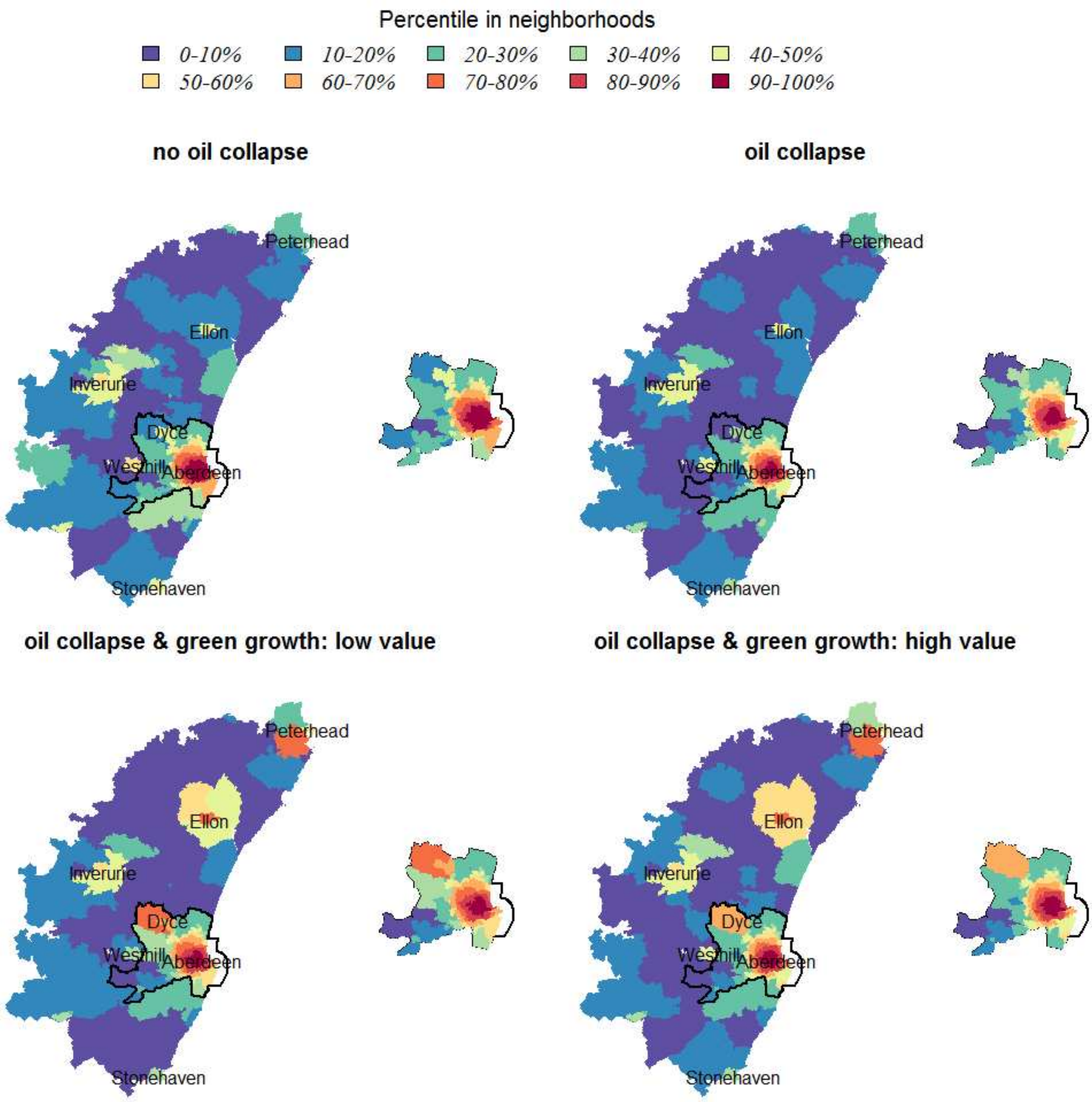

Figure 10 Employment opportunities across neighbourhoods under the four scenarios

Figure 11 shows the spatial distribution of both public and private services in Aberdeen, including supermarkets, restaurants, and retail stores, schools, hospitals and other social services. Since green industry is not service-based, Figure 6 reflects the emergent results of the relocation of service-based businesses in response to the growth of green businesses. We show that, under oil collapse, service provision has declined greatly, especially in Aberdeen city centre. The shrink in service reflect both the decline in population and their income.

The green growth has revived the service provision as well as shifted their spatial distribution. Under low value growth, the level of services has declined in the city centre, although to a less degree than that under oil collapse and no growth. At the same time, more services provision emerged in other areas, including the northern and southern suburbs of the city. Under high value growth, services provision has expanded more rapidly. Not only the service in the city centre and the suburbs has revived, but new service centre have emerged in Ellon and Peterhead. The quicker expansion of services under high value growth is largely due to the higher income in the green industry, which leads to higher demand for services.

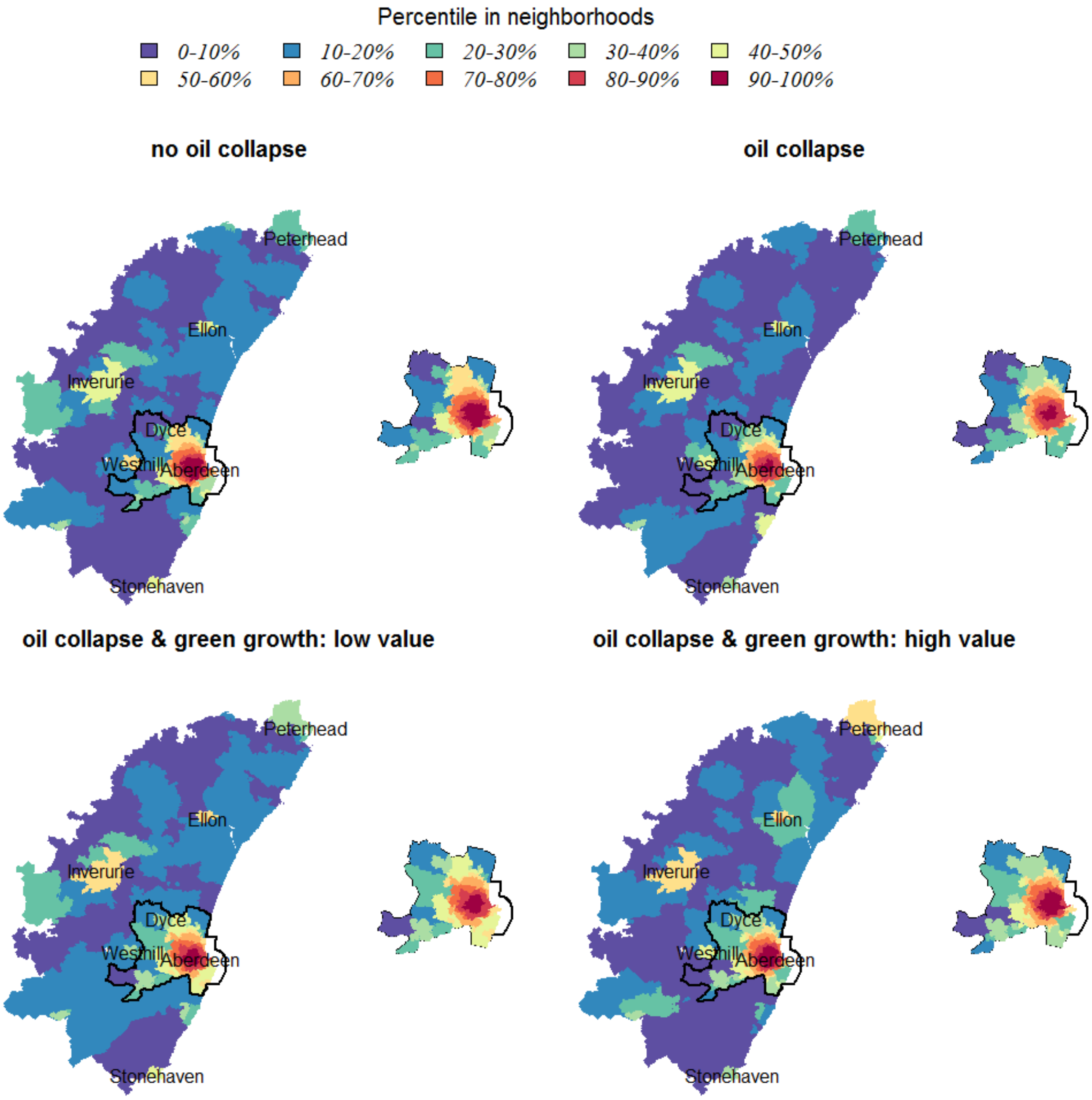

Figure 11 The level of services across neighbourhoods under the four scenarios

Figure 12 shows the spatial distribution of unemployment rate across data zones. Under the oil collapse scenario, even 20 years after the oil collapse, the unemployment rate in Aberdeen city centre is still much higher than under the no collapse scenario. As we have shown in the time-series analysis, the consequence of the oil collapse can last for a few decades. Moreover, areas with high unemployment rate are mostly concentrated in the city centre, which could lead to various social problems. Those problems in turn make the city a less desirable place to live and conduct business in, which will lead to even more unemployment. Once the vicious circle is triggered, it will require much more effort and investment to turn the situation around. Therefore, the green growth, especially the high value one, is essential in preventing the situation from happening and setting the city on a path of revival, as is shown in Figure 12.

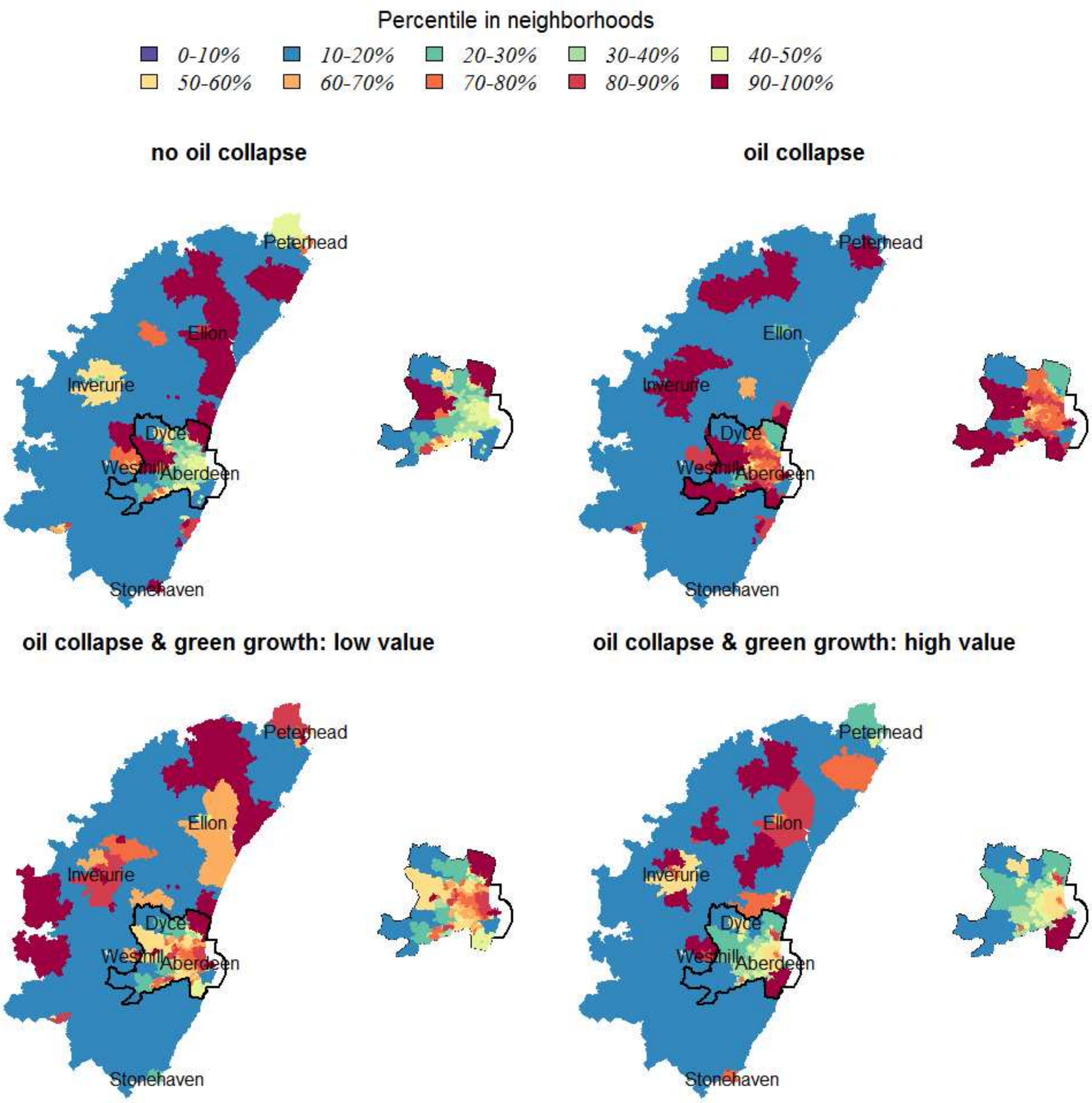

Figure 12 Unemployment rate across neighbourhoods under the four scenarios

Figure 13 shows the change of population (in percentage compared to pre-collapse level) in the neighbourhoods, which shows us a clearer picture of the migration patterns of the population. Under the no oil collapse scenario, most already densely populated neighbourhoods in the city centre see a further increase in population, indicating a trend of urban agglomeration. Under the oil collapse scenario, the immigration process into the city centre has slowed down significantly. In some areas in Aberdeen city, the population even declines by a large percentage, mainly because of the loss of job opportunities there.

With green growth, population growth is higher and as a result more regions see increase in population during the period. Although the population in Aberdeen city centre has increased, it is neighbourhoods in the development corridor near Aberdeen city centre as well as in Ellon and Peterhead that have seen the largest surge of population. Under low value growth, population growth occurs mainly in the two major towns situated in the development corridor, Ellon and Peterhead. Under high value growth, on the other hand, economic impact of green growth has extended beyond the boundary of the corridor. Population in areas in the northern and southern suburbs of Aberdeen city, and between Aberdeen City, Ellon and Inverurie have all increased.

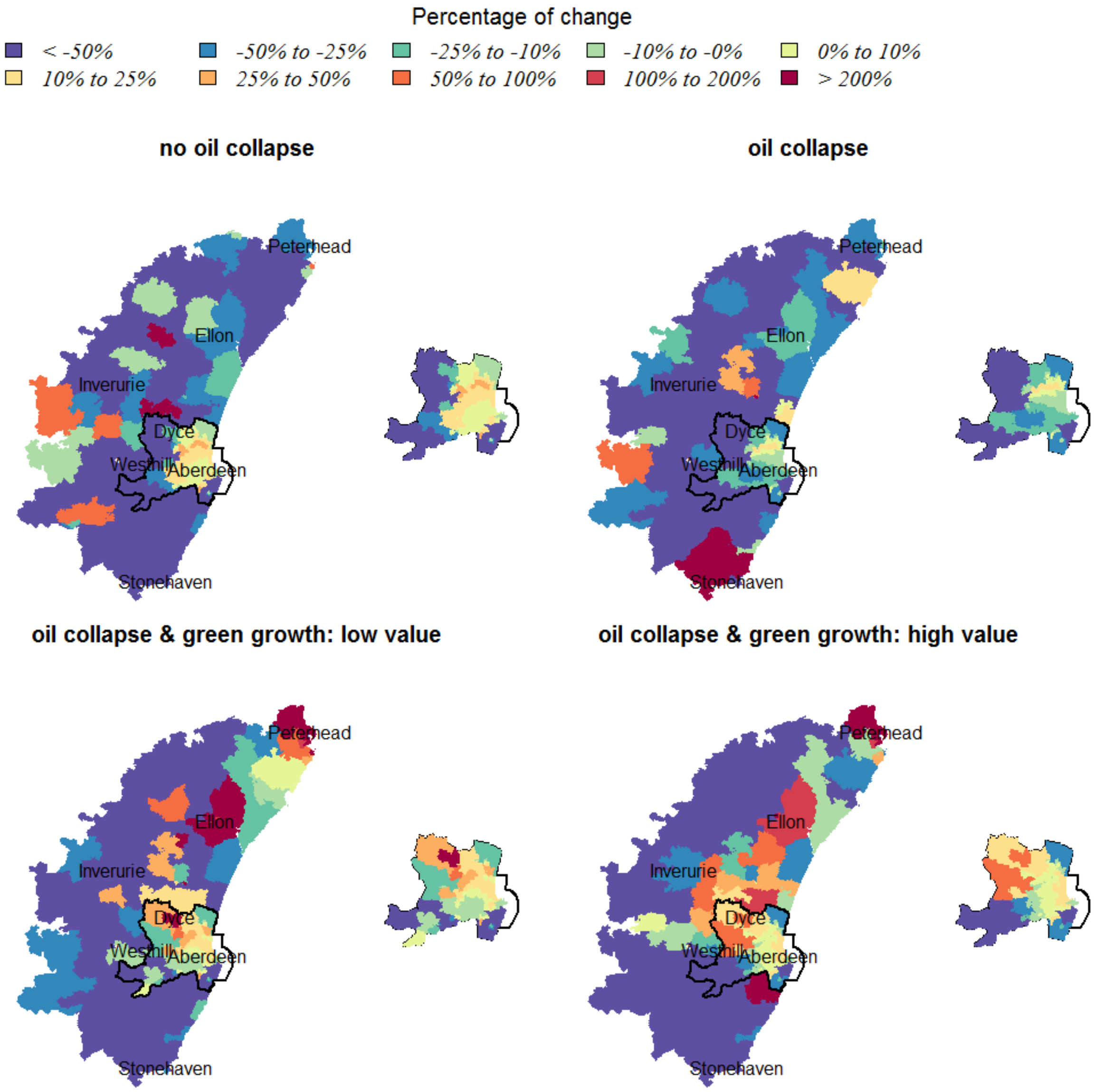

Figure 13 Population change across neighbourhoods under the four scenarios

5 Discussion

The results of the model demonstrate the potential magnitude of challenges and opportunities faced by Aberdeen at the moment. Although oil collapse might lead to devastating consequences such as declined population, high unemployment rate and deprived neighbourhoods, if managed well, it can be used as an opportunity to reshape the local economy and the urban structure. By strategically positioning the green businesses in the development areas, we are able to restructure the spatial distribution of households and businesses, and bring revival not just to the development areas, but also the areas surrounding them. In short, the possible decline of the oil industry does not need to be a catastrophic event, but rather an opportunity for the city to restructure its economy and neighbourhoods. It will, however require active industrial policy and strategic urban planning.

Pissarides (1992) shows the effects of a temporary shock to employment can persist for a long time when unemployed workers lose some of their marketable skills. We find similar enduring effect of oil collapse from the simulation. In the case of oil collapse without green growth, the unemployment rate remains high a few decades after the oil collapse first happens. The population remains much below the pre-crisis level two decades later. The former CBD becomes more desolate: the level of service, employment opportunities and income remains low in the central areas. The collapse of the oil industry does not only affect people in the oil related industries and their households, but also people in the service industries. The reduction in income and employment size leads to shrinkage of market size, which causes the relocation and shrinkage of the service industry, which further reduce income and market size.

Since the development of a city is highly path dependent, local government, firms and organizations may actually have a determining impact on the course of the transaction. As Simmie and Martin (2010) have noticed, The successful transition of Cambridge from a small service-based economy to a highly successful innovation centre starts with the formation of Cambridge Consultants, a technology consultant and incubator for technology start-ups, in the 60s, and the establishment of a science park granted and supported by the government in the 70s. Here we show that green growth, especially the high value one based on the existing labour force, expertise and supply chain infrastructure, supported by the councils in the form of development corridors such as Energetica can lead to hugely different future outcomes in the region.

A key issue in navigating through major crises and transitional period is time. The former oil industry employers have valuable skills, connections and know-how that could be used in the development of the green industry to help it gain a competitive edge over other regions. As previous research has shown, the re-employment has to happen relatively quickly before the human resources leave or depreciate (Edin and Gustavsson, 2008; Görlich and De Grip, 2008; Laureys, 2014). To recruit these knowledge workers, the new industry needs to be of relatively high value so that it can offer a wage high enough to attract skilled employees to stay in the area. Failing to do so quickly will cause a brain drain as the skilled employees find jobs elsewhere or give up looking for employment altogether. Unemployed workers will not simply sit and wait for the new green industry to be developed. Once a city has lost its skilled labour force, it will be much harder to recruit them from outside of the region when employment opportunities finally become available. The model results show that, although low value green growth can bring a moderate revival to the city, the recovery process will be slower and outcome less pronounced than under high value growth.

The reason that high-value green growth has achieved a better outcome is because with the competitive wage the green industry is able to re-employ former oil employees in the region soon after the oil collapse occurs. Research have shown that wage and price are relatively sticky (reluctant to drop) and often fail to respond sufficiently to changing economic conditions (Akerlof and Yellen, 1985; Barro, 1977). Prior to the oil crisis, Aberdeen city had already had one of the highest housing price, rent and wage in the UK (Geoghegan, 2014). Brezis and Krugman (1997) discussed the obstacles during structural changes: because of their previous prosperity, industries and households have already bid up local land rents, prices and wages, which could deter the entry of new business and employees. Therefore, the new industry that is to replace the old one needs to be high-value to offer a wage on par with the high local living expenses.

We have made several simplifications in the model. First, we assume that the housing price is fixed at the 2015 level (the oil crisis started in the third quarter of 2014) throughout the simulation, whereas in reality, the price will have dropped further as the oil crisis drags on and the market deteriorates. Allowing the local housing market to respond to market conditions may alleviate the effect of the oil crisis, as houses become more affordable. However, housing prices prove to be quite resilient: local real estate agents reveal that although it now takes much longer to sell a property and there is more room for price negotiation, so far transaction price in Aberdeen has only dropped slightly, partly because sellers want to avoid negative equity. We have also made simplifications in how people choose and switch between occupations. In the model, people choose occupations according to the current statistics (conditional on age and gender), and later in their career, decide whether to switch to another occupation (in the case of being unemployed) based on their skill and income level. In reality, people's careers can evolve over time, and so can the aggregated conditional statistics. They will also consider other factors than income when switching occupations.

Other simplifications include how people get married, have children, and get divorced (a probabilistic model based on gender, age and, in the case of marriage, distance between the partners' workplaces). Although we use the survey data and derive households' preferences from it, there must be other factors the family consider when choosing a house, as well as other idiosyncratic preferences that are not included in the survey. A person's life is the result of the complex interactions between life events, personal choices and characteristics, social interactions, as well as external factors such as a country's social, economic and political situation, culture and social norm. Therefore, it is extremely challenging to model a person's or a family's lifestyle with a holistic approach. To our best knowledge, this paper is one of the first attempts to do so. Our judgement regarding which simplifications to make is primarily based on their relevance and importance to the main purpose of the study, which is to model the urban transition process under the context of regional industrial structural change.

6 Concluding remarks

We develop an empirical, multi-layered and spatially-explicit agent-based model of an urban area that is in transition from an oil-based economy to a green one. We take a complex systems approach that incorporates the many interacting and interconnected components of an urban system and lifestyle: people, households, businesses, industries, neighbourhoods, and housing infrastructure. The model is underpinned by empirical data from various sources.

We find that the oil collapse could potentially lead to regional decline and recession, which can persist for a few decades. With green growth, however, the crisis may be turned into an opportunity to restructure the regional economy and reshape neighbourhoods. We find that the type of green growth matters, not only in directly creating businesses and employment opportunities, but also in affecting other related industries and businesses. The high value green growth will lead to better outcomes because it is able to retain local human resources and to take advantage of local expertise, connections and infrastructure. The location of the new businesses also has important implications in the development of neighbourhoods. Finally, we argue that industries, businesses and the local labour market are essential parts deeply integrated in an urban system. To understand the complex process of urban transition, urban models should consider both the household and the industrial aspects.

Acknowledgements

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Appendix

A. Overview, Design concepts, and Details (ODD)

In this section, we will follow the ODD protocol (Grimm et al., 2006; Grimm et al., 2010) to describe the "agent classes and attributes" and "Process overview and scheduling" of agent-based model.

A.1 Agent classes and attributes

The main agent class in the model includes person, household, business embedded in the industrial structure and housing infrastructure in Aberdeen.

A.1.1 Person

We simulate a person from the moment they enter the model either through birth or relocation into the area until the moment they leave the model either through death or relocation out of the area. As in real life, a person will take multiple roles at the same time: an employee, a spouse, a child and a parent. In the professional realm, a person will have one of the following employment statuses at any point of life: child (under 17), (university) student, employed, unemployed, inactive or retired. Being inactive means that the person is not actively looking for a job, either because they have been unemployed for an extended period or have given up looking, or because of external reasons, such as to take care of family members. People accumulate training and experience in an industry (more details in 0) through university training and work experience in that industry. They may also transfer their experience in a related industry to the current one. The wage a person can earn in the industry depends on the amount of experience and training they have in that industry. The more experience a person has, the higher wage they will have. A person may also become unemployed or inactive during their career. In the personal realm, people will take one of the following personal statuses: single (including divorced and widowed) and married (including co-habited). They may also have children. When the children grow up, most will leave the original household and start their own. As the simulation progresses, every person in the model grows old and, according to the conditional mortality rate based on age and gender, has a probability to die in each period. Table 3 lists the key attributes of the person agent.

Table 3 Person attributes ('Endogenous' means the value of the variable is determined in the model. 'Dynamic' means the value of the attribute changes over time)

Attribute	Type	Description	Endogenous?	Dynamic?
Age	Numeric	Person's age	N	Y
Gender	Male/female	Person's gender	N	N
Employment status	Child under 16, student, employed, unemployed, inactive, retired	Person's employment status	Y	Y
Employer	A business agent, or null if not employed	Person's employer	Y	Y
University	A university agent, or null if not a student	Person's university	N	Y
Current industry	An industry agent	Person's current industry	Y	Y
Experience	A vector of numeric values of experience (including training in the university) in all the industry	Person's experience in all industries	Y	Y
Annual income	Numeric	Person' annual income	Y	Y
Marital status	Single, married	Person's marital status	Y	Y
Spouse (if married)	A person agent	Person's spouse	Y	Y
Household	A household agent, with a vector of family members	The household the person belongs to	Y	Y

A.1.2 Household

Each person belongs to a household, which connects a person to their family members. We use survey data to populate the households in the region (more details in 2.2.2). The survey data contains various household types, including single person households, married couple with and without children, single parent households, households consisted of adult children and elderly parents etc. There are no standard households in the model, but 'clones' of actual ones in the sample (more details in 2.2.2). As the simulation progresses, households will merge, split and evolve. For example, when two people get married, they will leave their previous households and create a new one. When a married couple divorce, on the other hand, one will move out of the previous household and create a single-person one. When children become young adults between 16 and 24, some will move out of their original households. When a couple have children, the number of family members increases. We assume that all members in the household live in the same house, either rented or bought. Therefore, household is the unit for decision making of residential choice.

Households have heterogeneous residential preferences, and have different priorities with respect to the various aspects of a residence. The heterogeneous preference can be driven by the demographics of the households, the income and employment status of its members, or simply different tastes and lifestyles, defined as the sum of major life choices and events. For example, a family with school age children may give priority to school quality, while a family of retirees to quietness and health care. Some households may prioritize space over proximity to shops, whereas others may have the opposite preference. In the model, we use survey data on households' residential preference as the foundation from which we derive the households' residential preferences. As the model progresses, the member composition of a household, as well as the age, income, employment and marital status of its members will change over time. The households' residential preferences may therefore change as a consequence, leading to a decision to move house from time to time.

The local labour market conditions influence in households' residential choice in two important ways. First, they determine household income, which is the sum of the incomes of all the members. The household income determines the total budget for the purchase of a property. Only properties within the budget will be considered by the household. Second, because many people prefer to live reasonably close to workplaces, the location of the workplace of the family members as well as their employment status will affect their desirable residential location. Therefore, when (in the scenarios) Aberdeen moves from an oil-based economy to a green one, the shift in the local labour market will also change the spatial distribution of households, which will have a profound impact on the local labour and housing market.

We use an auxiliary class, residential preference, to represent households' heterogeneous preferences for residence. The residential preference class is a vector of numeric values each representing the importance a household assigns to different aspect of a house. The aspects are chosen to reflect the main considerations of a typical household when making residential decisions: price, energy efficiency, safety, green space, school quality, distance to work, public transport, access to shops, restaurants and other services, health care, and property size. Table 4 lists the attributes of a household agent.

Table 4 Household attributes (notation same as in Table 3)

Attribute	Type	Description	Endogenous?	Dynamic?
Members	A list of person agents	Household members	Y	Y
Household income	Numeric	Household income	Y	Y
House	House agent	The house the household lives in	Y	Y
House tenure type	Rented / owned	Tenure type of the house	Y	Y
Residential preference	Residential preference class	Households' residential preference	Y	Y

A.1.3 The housing infrastructure

As we said in the previous section, when choosing a house, a household will consider both the attributes of the house itself and the house's neighbourhood. In this section, we will describe the housing infrastructure in two parts: house attributes and neighbourhood attributes.

A.1.3.1 House attributes

The attributes of the house is encapsulated in the house class, which include its location, tenure type (rental or owner occupied), house type (flat, non-detached, and detached), the number of bedrooms, public rooms and bathrooms, whether the house has central heating, double glazing, garage or a garden. Each house also has a transaction record of all the previous transactions on the house from 1996. Each transaction record includes the transaction date and price. Table 5 lists the key attributes of the house agent.

Table 5 House attributes (notation same as in Table 3)

Attribute	Type	Description	Endogenous?	Dynamic?
Location	Postcode area	Geographic location	N	N
Current occupier	Household	Current occupier (N/A if unoccupied)	Y	Y
Tenure type	Rental or owner occupied	House's current tenure status	N	N
House type	Flat, non-detached, detached	House type	N	N
Num. Bedrooms	Numeric	The number of bedrooms	N	N
Num. Public rooms	Numeric	The number of public rooms	N	N
Num. Bathrooms	Numeric	The number of bathrooms	N	N
Central heating?	Logical	If the house has central heating	N	N
Double glazing?	Logical	If the house has double glazing	N	N
Garage or parking space?	Logical	If the house has garage or parking space	N	N
Garden?	Logical	If the house has garden	N	N
Transaction history	A list of transaction record	House/s transaction history	Y	Y

Attribute of transaction class	Type	Endogenous?	Dynamic?
Transaction date	Date	N	N
Transaction price	Numeric	N	N

A.1.3.2 Neighbourhood attributes

A neighbourhood is a residential area that shares common characteristics such as public school, public transport, hospitals and retail centres. The Scottish government has defined 6976 data zones in Scotland, which is the key small-area statistical geography in Scotland. Each data zone has between 500 to 1000 households and is considered to be a "common, stable and consistent" small-area that contains households with similar social characteristics (SIMD, 2016). In 2011, the Scottish government evaluated all data zones in the seven domains of employment, income, crime, housing, health, education and accessibility. An overall Scottish Index of Multiple Deprivation (SIMD)[6] score is derived from scores in all domains for each data zone to reflect the level of deprivation in the area. In this study, we define neighbourhood as a data zone. As can be seen in Table 6, in the model, some domains of the neighbourhood/data zone are endogenous and subject to change during the simulation. Table 6 lists the attributes of the neighbourhood/data zone class.

Table 6 Neighbourhood/data zone attributes (notation same as in Table 3)

Attribute	Type	Endogenous?	Dynamic?
Geographic area and location	Polygon	N	N
Employment score and rank	Numeric	Y	Y
Income score and rank	Numeric	Y	Y
Crime score and rank	Numeric	Y	Y
Housing score and rank	Numeric	Y	Y
Health score and rank	Numeric	N	N
Education score and rank	Numeric	N	N
Accessibility score and rank	Numeric	Y	Y

A.1.4 Business

In this model, we define a business as any organized entity that provides goods and services to the public or other businesses. A business can be a large oil company, a chain supermarket, a small local café, the city council, a post office or a church. A business has the following attributes: the industry it belongs to, the number of employees it has, and its geographic location, and its aspired growth rate. Although in reality a business can span across multiple industries, in the model we assume that each business has a core service or products that belongs to one industry. Service-based businesses set their aspired growth rate based on the growth of market size relative to the number of competing businesses of the same industry in the neighbourhoods. Based on the industries they are in, businesses have different target groups (see Table 1). The total market size is the sum of the income of the people in the target group who live or work in the neighbourhood. Non-service businesses remain the same size unless otherwise specified in the external scenarios, which we will discuss in Section 3. Once set their aspired growth rate, businesses make recruitment decisions accordingly.

When market size shrinks significantly relative to local competition, service-based businesses will consider relocation to more preferable neighbourhoods where market size relative to competition is high. Non-service businesses, on the other hand, do not change their location. The employees of a business may change every period due to new employees being recruited, current employees quit, retire, die or made redundant. Table 7 lists the key attributes of the business agent.

[6] Scottish Index of Multiple Deprivation 2016 http://simd.scot/2016/#/simd2016/BTTTTTT/12/-2.1990/57.1510/

Table 7 Business attributes (notation same as in Table 3)

Attribute	Type	Description	Endogenous?	Dynamic?
Industry (as in Table 1)	One of the 18 industry agents	The industry the business belong to	Y	Y
Employees	A list of person agents	The employees of the business	Y	Y
Location	As postcode	Geographic location	Y	Y
Growth rate	Numeric	Business's aspired growth rate	Y	Y

A.1.5 Industry

An industry has the following attributes: whether it is skilled, whether it is service-based, and similar it is to other industries, the income and gender-age distribution of the industry. The skill level represents the level of training and education needed for a person to work in the industry. Skilled industries require more training or experience than non-skilled ones. A person without the minimum training and experience requirement in the industry cannot be hired by that industry. Moreover, when unemployed, people with experience in a skilled industry will find it easier to get a job elsewhere. An industry can be service-based or non-service-based. The former prefers to be close to the market, the latter is indifferent about location. The similarity vector is a vector of indexes between 0 and 1 that represents the extent to which knowledge and experience can be transferred from the current industry to others, with 0 meaning no transfer and 1 meaning 100% transfer. By definition, transfer rate is 100% in the same industry. During the simulation, new industries could be created, as is the case of the green growth scenario (more details in Section 2.3).

The income distribution is a mapping from percentile (from 1 to 100) to annual income (before tax), which represents the overall wage level and distribution in the industry. The income distribution might change when an external economic shock happens, such as an oil collapse that lowers the income level of the oil and gas industry. The gender-age distribution is a mapping from gender-age combination to the percentage of employees in that industry who belong to the gender-age group. The initial gender-age distribution for all the industries is derived from employment data. Gender distribution across the industries will also be reflected in people's career choice. When choosing university majors, people are more likely to choose the industries in which their gender is over-represented. As we will show later, the initial income and gender-age distribution differ vastly across industries. Table 8 lists the key attributes of the industry agent.

Table 8 Industry attributes (notation same as in Table 3)

Attribute	Type	Description	Endogenous?	Dynamic?
Skilled?	Logic	If the industry is skilled	N	N
Service-based?	Logic	If the industry is service-based	N	N
Similarity index vector	A vector of indexes between 0 and 1	Similarity/knowledge transfer level to other industries	N	N
Income distribution	Mapping table	Mapping from percentage to annual income	N	Y
Gender-age distribution	Mapping table	Mapping from gender-age to percentage	Y	Y

A.2 Process overview and scheduling

Each period represents a month in real time. The model is open, meaning that in each period, people, households and businesses may enter and exit the model. During each period, changes and updates will happen in the following areas: a person's private life, a person's work life, household, business and industry, and finally, neighbourhood, which are also connected with each other. In the following sections we will discuss the process overview and scheduling.

A.2.1 A person's private life

During each period, all people grow older by a month. Depending on a person's gender and age, there is a probability that they will get married (if they are not already) or divorced (if they are married), have children or die, which are all modelled in a probabilistic function based on demographic data from Scottish census (more information see Section 2.2.3). We define being married as being cohabitant as a couple, regardless of legal marital status. The chance that two people will get married depends on their age and the distance between their homes and workplaces. People who are closer in age, and have homes or workplaces that are closer geographically are more likely to get married. Among married couples, there is a small probability that they will get a divorce and separate into two households in each period. We also use probabilistic models for the event of death and giving birth based on the mortality and fertility rates conditional on gender and age. Figure 1 shows the process overview of a person's private life.

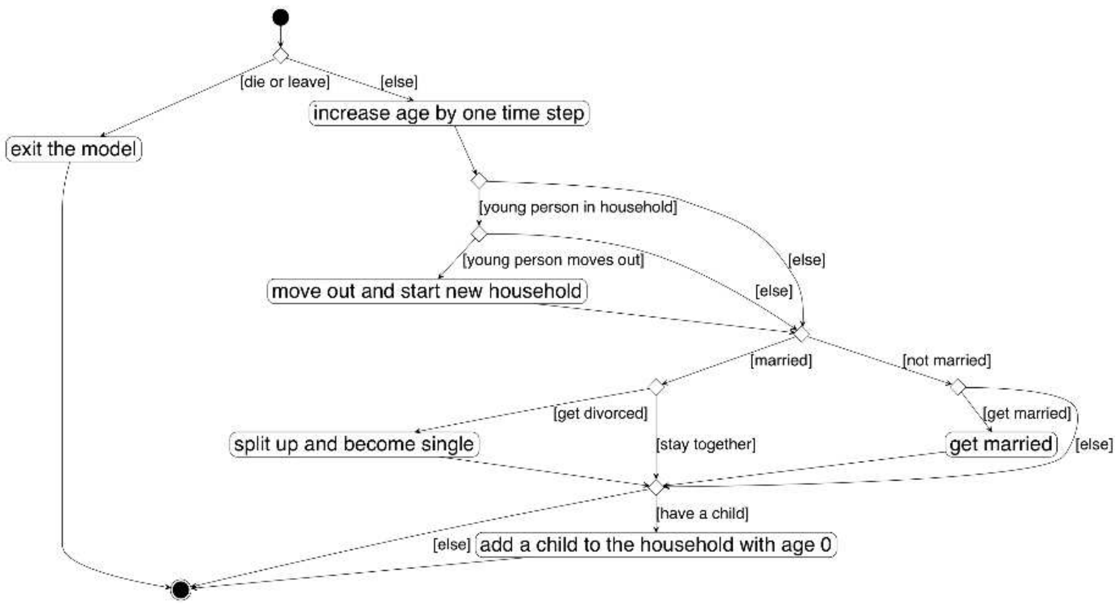

Figure 14 Process overview of a person's private life

A.2.2 A person's work life

In each period, people may become a student, employed, unemployed, inactive and retired, given the age, gender and the current employment status of a person. People can only be employed if they are between age 16 and 74. Employees can become unemployed if the business decides to downsize and make them redundant or fire them if they fail at the job. A person can also quit voluntarily. The reasons an employee quit can be endogenous, such as the relocation of their households, partially endogenous, such as pregnancy, or exogenous, such as change of interest. For each period a person is employed, they gain experience in the industry they are currently working in. Employees between 60 and 74 may decide to retire.

In each period, unemployed people might become employed by a business if the business is recruiting. A person needs to meet the minimum experience/training requirement to be hired by an industry. Skilled industries have higher requirement than unskilled industries. People with more experience will be given priority in recruitment in a skilled industry, but not in an unskilled one. If people cannot be re-employed in their previous industry locally, they will also consider jobs in another industry, as well as jobs elsewhere. When offered a job in another industry, the unemployed person will compare the median income of their previous and potential industry. If the income in the potential industry is significantly lower than that in the previous industry, the person will reject the job offer. However, the longer a person stays unemployed, the lower the income threshold above which he/she will accept the job offer.

The chances that an unemployed person will find a job elsewhere depend on the person's skill level. We assume it is easier for a skilled person to find a job elsewhere than for an unskilled one. When a person finds a job outside the area, they need to decide if they will take the job. For a married person, in addition to the income threshold, their decision to accept the job also depends also on the employment status of their spouse. If their spouse is unemployed, retired or inactive, the person will take the job and move the entire household out of the city. On the other hand, if their spouse is a student or employed, they will compare the skill level of the industry their spouse in with the industry of the potential job. If the potential job is unskilled and industry of the spouse is skilled, the person will reject the job offer. If, on the other hand, the potential job is skilled and the spouse's job or major is unskilled, the person will accept the job offer. Finally, if both the potential job and the job of the spouse are skilled, the chance of job move is half. A single unemployed person always accepts a job offer and will move out of the city. Finally, an unemployed person may give up and become inactive, meaning that they will no longer look for a job and be inactive in the job market. Figure 15 shows the process overview of a person's work life.

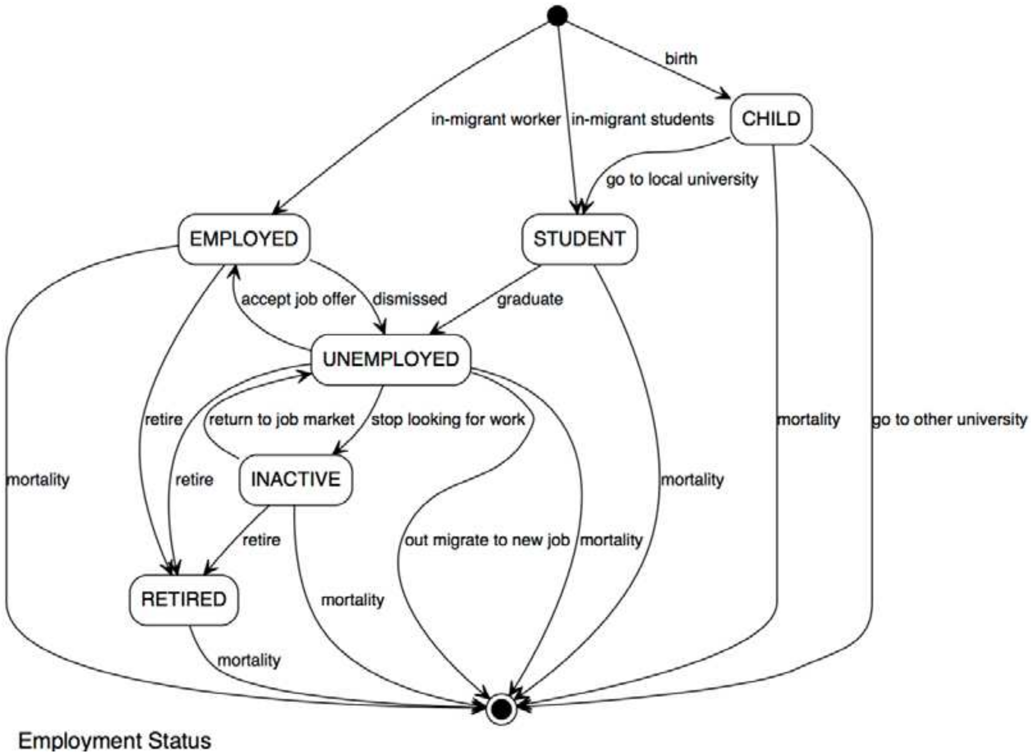

Figure 15 Employment status update of a person

A.2.3 Household

As people change their jobs, employment status, income, age and marital status, they affect their households and its residential choices, as their current house may no longer meet their needs and aspiration. For example, household with new-born children may need more space and give higher priority to school quality; and households with children starting university and leaving home may want to downsize the house and give less priority to school quality. Changes in job and income may also inspire the households to move, to be closer to work, and/or to upgrade or downgrade the house as their income changes. A household may also want to change their house tenure: a renter may want to become a homeowner and vice versa.

Households in the model are matched to a "reference household" from the survey sample (see 2.2.2) based on the family composition and living situations, their members' demographics, employment status and income. We then retrieve households' residential preferences from data on the reference household from the survey sample. As households evolve and change overtime, so are their reference household and their residential preference. They will evaluate their housing situation and decide if they aspire to move house. If so, households will evaluate a number of unoccupied houses within their budget and relocate to the one that most suits their preference. The evaluation of a house is based on the house attributes and neighbourhood quality, as well as the priority the household assigns to them.

A.2.4 Business

In each period, a business adjusts its aspired growth rate, employees, their wages and the location if it is service-based. A business may decide to expand, keep the status quo, or shrink depending on the market size and conditions. A business that decides to expand will need to recruit new employees, whereas a business that decides to shrink may make employees redundant. A business will also recruit replacements for employees who have retired or quitted. Finally, a business will fire any incompetent employees and replace them with new ones. Incompetent employees make up a small percentage of total employees.

If a business is service-based, it will want to be close to the market that it serves. Market size is defined differently by different industries. For example, for non-tertiary education, the market is the number of school-age pupils living in the neighbourhood. For other industries such as retail and catering, market is the purchasing power of people who live or work in the nearby neighbourhoods (see Table 1). Service businesses adjust their sizes according to the market size relative to competition in the nearby neighbourhoods. They expand when the market size relative to competition grows, and vice versa. When the market size relative to the competition in the nearby neighbourhoods shrinks significantly, a service business will consider relocate to another location.

Once the business has decided on its location and growth rate, it will try to recruit new employees if needed. We assume that businesses in a skilled industry will only recruit people with at least three year of training or experience. A business in an unskilled industry does not have such requirement. When facing multiple qualified candidates, a business in a skilled industry will give priority to those with more experience. A business in an unskilled industry, on the other hand, has no such preference and will pick a candidate randomly. It will also adjust the wages of its employees. The wage of an employee depends on the overall industrial wage structure and their experience, which is derived from empirical data and subject to change according to economic conditions and scenarios as in Section 3. It reflects both the wage level and wage distribution in that industry. An employee's experience (including training in the university) determines their positions in the wage distribution of the industry. The longer the experience, the higher the wage is in the distribution.

A.2.5 Neighbourhood evolution

As people, households and businesses change status and move location, they inevitably influence the neighbourhood. For example, the relocation of a business to a neighbourhood will create new jobs in that neighbourhood, but also change the service level and the market competition there. The relocation of a household to a neighbourhood will influence its mean income and safety, as well as the market size there. As a result, the neighbourhoods are constantly evolving. The domains of a neighbourhood, including employment, income, crime, housing and accessibility are influenced and changed by the relocation decisions of household and businesses. The domain scores and ranks of the neighbourhoods are updated in each period.