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Investigating Agent Based Models for testing the effects of Carbon Taxes on the Information and Communications Technology Market with respect to Small and Medium Sized Enterprises in the United Kingdom

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Summary

At a time when climate change has become an accepted risk to civilisation, governments are developing and implementing policies designed to reduce the impacts of anthropogenic greenhouse gas (GHG) emissions. These can include “command and control” directives. However, in free market economies, such as the United Kingdom, there is a preference for a lassie faire approach with taxes and incentives designed to shape the market rather than direct government intervention.

This thesis examines the feasibility of using agent-based modeling techniques for predictive analysis with respect to the application of carbon taxes on electricity consumption in the context of wider societal objectives and scenarios – particularly in the procurement of information and communication technology (ICT) equipment and services by small and medium businesses (SMEs) in the United Kingdom. In doing so it provides an area of novel research. With more than 2% of greenhouse gas (GHG) emissions associated with the usage of ICT and with that proportion expected to grow, it is an important sector to target with emission reduction strategies. Testing these strategies in simulation prior to application to the market place is important to policy makers. Normally, policy makers wish to reduce the risk of implementing policies that would not achieve the desired goals and or harm the economy. Agent-based modeling potentially offers policy makers valuable insight into probable emergent market behaviour from a “bottom-up” methodology that better suits free markets that contain millions of SMEs.

This thesis applies a multidisciplinary problem solving approach, including microeconomics, agent based modeling and policy research, to examining potential market responses to carbon taxes such as the Climate Change Levy (CCL); the UK’s primary carbon tax designed to reduce carbon emissions produced by SMEs. Areas of novelty in the thesis include the use of agent based models to examine the effects of carbon taxes on the behaviour of SMEs and the use of ICT as a factor production with the SME agents themselves.
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My family and friends have been an enormous benefit and a pillar of patience when things were going badly, for which I am eternally grateful. And I dedicate this body of work to my Mum.
I confirm that the submitted work is my own work and that I have clearly identified and fully acknowledged all material that is entitled to be attributed to others (whether published or unpublished) using the referencing system set out in the programme handbook. I agree that the University may submit my work to means of checking this, such as the plagiarism detection service Turnitin® UK. I confirm that I understand that assessed work that has been shown to have been plagiarised will be penalised.
Glossary of Terms

Terminology as used in the body of this thesis document:

ABM: Agent-Based Model(s)
CBA: Cost Benefit Analysis
CBI: Confederation of British Industry
CCA: Climate Change Agreement
CCL: Climate Change Levy
CDM: Clean Development Mechanism
Cloud: ICT service provided by a third-party firm to SMEs
CRCEE: Carbon Reduction Commitment for Energy Efficiency
Datacentre: Hub for high performance servers for client computing and storage.
DECC: Department for Energy and Climate Change
EC: European Commission
ETS: Emissions Trading Scheme
EU: European Union
GBP: Great Britain Pound
GDP: Gross Domestic Product
GHG: Greenhouse Gas
Hardware: ICT equipment (e.g. server) owned and operated directly by the SME.
ICT: Information and Communications Technology
ICT4EE: ICT For Energy Efficiency – Industry lobby group
ICT Provider: Firm that sells either “cloud” services or hardware equipment.
IMF: International Monetary Fund
IPCC: International Panel on Climate Change
ITU: International Telecommunications Union
KPI: Key Performance Indicator
LCA: Life Cycle Analysis
MNO: Multinational organisation
MRS: Marginal Rate of Substitution
MRTS: Marginal Rate of Technical Substitution
N/A: Not Applicable
NGO: Non-Government Organisation
ODD: Overview, Design and concepts and Details
ONS: Office of National Statistics
PCF: Product Carbon Footprinting
Platform: Combination of hardware and software designed to perform ICT functionality.

ROC: Renewable Obligation Certificate

ROI: Return on Investment

Server: Physical or virtual machine for the storage and distribution of files.

SLA: Service Level Agreement

SME: Small to Medium Enterprise (defined as 10 to 249 employees)

Solution: Integration of hardware and software that provides user functionality.

TLA: Three Letter Acronym

UNEP: United Nations Environment Programme

WTO: World Trade Organisation
Chapter 1: Introduction

With the publication of the United Nations' Intergovernmental Panel on Climate Change (IPCC) report on the risks of climate change in 2014, there was renewed impetus on policy makers around the world to enact policies designed to modify and adapt the behaviour of citizens to mitigate the effects of societal emissions of greenhouse gases (GHGs) into the atmosphere. The Information Communication and Technology (ICT) industry contributed over 1% of global GHG emissions in 2007 and this has been rapidly growing. Due to a developing world economy and increased user demand (from, for example, the increased use of datacentres and personal devices) this is set to rise to 4% by the year 2020 (Malmodin, et al, 2010). Therefore, reducing GHG emissions from the ICT sector and using ICT to leverage indirect GHG reductions in other sectors (e.g. transport, energy distribution and manufacturing) through efficiency gains is a priority for government policy makers. It is also of interest to the ICT industry itself – market players, such as the large multinational ICT firms, are keen to develop a competitive advantage over rivals and win market share (Walsh, G., 2010.)

The United Nations Environment Program (UNEP) issued guidance in 2011 that policy makers should design their environmental policies to maximise environmental protection or remediation, while limiting the impacts on human wellbeing. In line with directives from the European Union (EU) and domestic political will in the United Kingdom the Department for Energy and Climate Change, and its predecessors, have designed a series of policies that are intended to make the UK economy more energy efficient as well as reduce GHG emissions (Gillard, R, 2016). On a global level the advice issued by the UNEP was written in a context of encouraging sustainability objectives as well as reducing greenhouse gas emissions. The term sustainability in this document is as defined by the Brundtland report as “sustainable development is the kind of development that meets the needs of the present without compromising the needs of future generations to meet their own needs” (Barnaby, F. 1987). This principle is explored further in chapter 2, it is important to explore other aspects of sustainability as well as the issue of climate change and greenhouse gases as they are complementary issues and provide a context for the political and economic impetus for carbon taxes designed to
reign in GHG emissions (Nordhaus, W.D. 1992). As explained in greater depth later in this thesis, climate change is an economic issue as well as an environmental one (Nordhaus and William, 2010). Also, the role of information technology within the principles of sustainable development (for the means of this document the term is interchangeable with the word sustainability) is multifaceted and is seen by some as almost a magic bullet. There are therefore expectations that improvements in ICT will allow for remote working, teleconferencing, energy efficiency gains, smart metering, traffic decongestion; the list of possibilities is great. However, ICT is also a primary consumer of resources, in manufacture, infrastructure, distribution and usage. In all of these aspects there is political pressure on the industry to reduce its own consumption as well as provide energy and resource efficiency improvements for other sectors and users (Achachlouei and Hilty, 2015). How carbon taxes help to achieve this in context with other drivers for change is explored later in the chapter and in the thesis.

In the research conducted for this thesis a simple carbon tax (i.e. a tax added to the consumption of electricity produced from carbon emitting sources) was used as the starting point as a policy instrument. It was then modelled in computer simulation to assess the response of the ICT market to government intervention in the electricity market – a key overhead for ICT users. This was an area of academic novelty that the thesis pursued. There is scope to further the research by simulating the effects of alternative taxes, incentives and even tradable permit schemes. These would require an expansion of the Set 2 Java models developed for this thesis. One of the primary advantages of using an object orientated language such as Java is the flexibility it offers to create additional detail as required. In chapter 6 at the end of this thesis these alternative research ideas are discussed in further detail.

The primary focus of this thesis was to assess the usefulness of agent based models (ABMs) to analyse the effectiveness of environmental policies, particularly a carbon tax. It was also how ABMs could be used to simulate the decision making process in ICT procurement, by applying a combination of accepted techniques to model aggregated microeconomic interactions between agents and their virtual worlds that result in an emergent behaviour. For example, Epstein and Axtell’s research work into artificial societies (Epstein and Axtell, 1996). The first decision examined by the research regards a common scenario for ICT Managers; the choice between upgrading their existing hardware installations or subscribing to a service provided by a third party. This third-party service is likely to be managed remotely and provide what is commonly referred
to as a “cloud” solution. As part of the research methodology a comparison is conducted of analytical methodologies that could be used in place of an Agent Based Model - in particular a time series econometric analysis and cost benefit analysis (CBA). In the development of the models there was an iterative process to determine the relevant parameters; such as trust in the technology, carbon tax level, legacy effects of previous systems and costs. These were factored into the development of the first ABM simulations. The first generations of simulations (Set 1) were written in NetLogo 5.05, a high-level programming language written in Java purpose built to write agent based models. However, it was replaced with writing original Java code to maximise the effectiveness of using microeconomic principles of the firm in the Set 2 models. This was something that NetLogo could not easily be adapted to do and it was more efficient to write code in Java specifically around the use of profit maximising firms that use ICT as a factor of production. Doing this also provided an area of novelty for the research. At the time of writing there has not been any published research using ABMs where agents used profit maximising firms and ICT as a factor of production. There is more detail on this topic later in the thesis in the methodology section, chapter 4.

Preliminary results indicated that there is huge scope for ABMs in the analysis of environmental policy effects on the ICT market. This is another area where this research provides novelty when compared to published academic material. More research could be done to increase the realism and predictive qualities of the ABM models developed. The analysis of the early NetLogo models indicated a very high level of tax (>100% of electricity costs) is required to produce a noticeable shift spending by IT managers. They require very high taxes to select the less GHG emitting “cloud” option - these ICT solutions are less GHG emitting on a per user basis when systems are optimised correctly with the correct use of virtualisation and energy management (Kusic, D, et al, 2009). In the simulations, the marginal rate of technical substitution between the procurement of hardware and “cloud” solutions were also affected by the level of trust the IT managers had in the options, not just the relative costs. The marginal rate of substitution was determined from information gained from the semi-structured interviews with industry professionals, more detail on this is provided in the methodology in chapter 4. These interviews provided a valuable insight into the potential spending patterns of the marketplace. The interviews also helped develop a hierarchy of parameters and their relative importance to typical SME ICT professionals.
The results of the simulations were compared to real life sales data from ICT provider firms such as Rackspace and market surveys from Gartner, discussed in more detail in the results and discussion in chapter 5. Rackspace concluded that over 60% of their SMEs clients saw notable operational cost reductions, due to improved hardware optimisation per user. The Set 2 models (written in Java and using ICT as a factor of production) also concluded that the UK’s carbon tax would need to be around GBP 0.50 per kWh of electricity to illicit a strong market shift from hardware to “cloud” services with current typical IT Manager preferences.

Future work could include the addition of different types of agents into the model; government agencies, users, consumers and IT managers. Adding IT managers as a separate entity within SMEs would be of particular interest as their decision making could be swayed, for example, by differing objectives dependent upon their job security or key performance indicators.

The potential effectiveness of environmental policies before they are implemented as well as how policies are born out of global, regional and national sustainability objectives was researched as part of this thesis project. This was compared to other established techniques such as researching historical time series data using regression analysis techniques, a well-established method of assessing the efficacy of policies after they have been implemented (Imbens and Wooldridge, 2009). In this thesis, there is an appreciation of the desire of policy makers to have predictive analysis to understand the likely outcomes of an environmental policy, for example the likely market response of a carbon tax on electricity (the Climate Change Levy is aimed at deterring the consumption of electricity produced from fossil fuels). As a result of the Set 1 models (research into the feasibility of using ABMs for predicting the results of carbon taxes), the title and main research question was evolved to: *The application of Agent Based Models to testing the effects of Carbon Taxes on the Information and Communications Technology Market with respect to Small and Medium Sized Enterprises in the United Kingdom.* This title was chosen after scanning the literature for previous research by others and a search for novelty with a desire to combine interests in green computing, sustainable industry, information technology and market forces.

A description of the workings of the series of algorithms running the simulations used to conduct the preliminary research is included to explain the evolution of the thinking process during the research conducted for the PhD. Assumptions made during the Set 1
building process changed over time as the model was challenged and refined in an iterative process and helped to reformulate the theoretical principles that were applied. For example, a much greater emphasis was placed on the marginal rate of technical substitution between the two options under examination.

In chapter 2 the literature review describes the way in which environmental policy interacts with the ICT industry – particularly in the European Union (EU). It also pieces together the logical evolution of where research thinking is with respect to environmental policy, market influence and agent based modelling and is discussed in more detail in chapter 3.
Chapter 1 References:


Chapter 2: Literature Review

2.1 Introduction to Literature Review

In this section of the thesis, academic literature is discussed to develop the context for the research models. Academic, commercial and governmental publications were analysed, themes explored and influence assessed. The original scope of the EngD project that preceded this PhD project was to examine the drivers for energy efficiency within the ICT industry. This proved to be a useful starting point for examining how environmental policy, in particular a carbon tax, can affect ICT purchasing behaviour.

Following the review of environmental policy and drivers the focus of the literature review then turned to quantitative methods in assessing policy efficacy, where the relative merits of econometric modelling techniques were reviewed.

2.2 Environmental Policy from the Perspective of the European Union and United Kingdom

Here European Union and United Kingdom policy directives and programmes are discussed including how they interrelate with GHG emission reduction, the ICT industry and the principles of sustainability. There is also a discussion of how international treaties may affect the environment, marketplace, policy makers and the ICT industry. This review provides the background for why the research topic of this thesis is of academic, commercial and governmental interest.

2.2.1 Use of International Treaties

One of the key difficulties with creating international agreements is the perception that one or more sides may lose out economically, politically and even environmentally, while other nations could be seen to gain disproportionate benefits. Even the World Trade Organisation (WTO), as an independent body could have difficulty appearing impartial to its members (Luo, Y 2007).

The Montreal Protocol, banning the use of CFCs gases, much touted as a historic success story in international cooperation, had to make significant concessions to allow
emerging markets, such as China’s, an opportunity to shift to alternatives without adversely affecting their economic growth (Vakil et al, 2006). This again highlights the issue that nations should not be seen to lose out economically; otherwise agreements are unlikely to be ratified.

The expectation that there should be continued economic growth, it could be argued, is a key hurdle to international environmental agreements, due to the perception that mitigating environmental issues has an adverse economic impact on growth (Jayadevappa and Chhatre, 2000). Also, that the economic impact is not necessarily equally shared and can result in an unfair trade advantage of one nation against rivals. Examples of this conflict can be relatively obvious, for example in Malaysia and Brazil the rainforest is under pressure from farmers and ranchers looking to tap into the economic potential of the land (Wright, S.J. 2005). Typically, this would be from grazing cattle or the growing of palm. These activities directly and indirectly release carbon into the atmosphere, reduce biodiversity and reduce the carbon sink potential of the earth. Many of these effects cross borders, so even though the nation state undertaking the activity receives the benefits their neighbours also shoulder some of the costs (Parrenas, 1997). The Climate Change Levy modelled in this PhD thesis is an example of UK government policy designed to help meet treaty objectives and obligations.

This issue of cross border effects can lead to neighbouring nations attempting to exert political and economic pressure on the state causing the environmental destruction. For example, China is frequently under pressure from the USA and other nations over its consumption of resources and its track record on pollution (Foot, 2006). However, the situation there is complicated by the fact a significant proportion of that consumption and pollution is caused in fact by the manufacture of goods for, often western, consumers outside of China (Cheung et al, 2009). This issue has led to a debate as to how to attribute cause, or perhaps blame, of environmental impacts of nations. While the issues of international treaties were not directly modelled in the Set 1 or Set 2 simulations conducted for this PhD thesis, they did help create the conditions necessary for the UK government to introduce the Climate Change Levy, which is included as a variant in the models.

A lack of a perceived time pressure can also be a hurdle to creating international agreements, different nation states can have different views as to how urgent an issue is. For example, it could be argued that the US had a more laid back approach to the issue of
climate change than the UK (Reynolds et al, 2009). This could be down to domestic political agendas, but it is also dependent upon how widely accepted the scientific argument is, in this case the evidence for anthropogenic climate change is strong (Serreze et al 2000).

In the case of the hole in the ozone layer, caused by the use of CFCs, the scientific community successfully took the lead and politicians were relatively quick to accept the evidence. Therefore, the Montreal Protocol had fewer hurdles to overcome than more recent agreements involving greenhouse gases (Daniel et al, 2012). The fact that the economic impact was also significantly lower is also likely to be a key factor. If similar acceptances of anthropogenic climate change were to occur then the ICT market would be very significantly influenced by the likely international treaties that would emerge on the consumption of energy and the emissions of greenhouse gases. This would also probably change the nature of the Set 1 and Set 2 simulations developed for the research phase of this PhD project.

2.2.2 Eco-design

The phrase Eco-design is something that is open to broad interpretation. However, in the context of this thesis, it refers to the Eco-design directive from the European Union. This directive is an example of a “command and control” policy where government goals translate into targets or regulations for industry agents, such as the ICT sector, to adhere to or face sanctions (for example not being allowed to sell offending products in the market place). Within the European Union (EU) different legislative mechanisms will have differing levels of influence upon the market for computing devices and services. For example, the Eco-design directives of the European Union have a direct bearing upon the actual performance specifications of the devices permitted to be sold within the EU and therefore a direct influence upon the market (Zogolli, H. 2015). Primarily, the Eco-design directives have set parameters on the energy consumption of devices in different modes of operation, including stand-by. If a device does not meet the performance parameters dictated, then the manufacturer is not permitted to sell it within the EU. Originally, the European Commission when drafting the original Eco-design directive had considered the performance spectrum of the hardware devices already on the market place at the time and set the criteria accordingly. The first Eco-design directive was not intended to limit consumer choice and therefore the performance criteria were relatively wide (Wang et al, 2015). It is intended, however, that performance specifications will be tightened as time goes by with the expectation
that ICT manufacturers are motivated to improve their products or risk losing access to the EU marketplace. For example; in its original form the Eco-design directive came into being in 2005 as the Energy-Using Products (EuP) Directive 2005/32/EC, later amended in 2008 and recast in 2009 to include "Energy related Products" (ErP) in 2009 (The Eco-design directive (2009/125/EC)). A working plan initiated in December 2012 extended the scope of the directive to include network systems (data storage and enterprise servers) as well as further the usage of eco-labels. The remit and influence of the directive covers a significant proportion of the goods ICT firms manufacture or, by indirect extension, services they provide (because ultimately, they will rely on hardware to deliver the services) (Wang et al, 2015).

Private firms sometimes claim policies such as the Eco-design directive are anti-competitive and potentially favour some firms over others as performance specifications can be based on existing products. If the product mix of one firm more closely fits into the new Eco-design performance regulations they gain a competitive edge over firms that are also bidding for government contracts who do not meet the regulations. This can feed into the wider market as well as Eco-design directives are treated as "best practice" by procurement professionals in the private sector (Schischke et al, 2006).

Regulations are costly for governments to enforce and can make it harder to cooperate with private industry in forums such ICT4EE (an industry group designed to increase communication between the EU and ICT firms on the topic of energy efficiency and sustainable development) (Innes, R. 2004). Industry groups often lobby hard to be engaged with in the development of regulations, to ensure that the final regulations are not too costly for them to adapt to, are fair across the industry and are physically possible. (Svendsen, G.T. 1999). The term energy related products (ErP) was used to signify that the scope of the directive had been expanded to include products that could affect energy consumption, (for example double glazing and insulation), not only products that draw power. This family of directives have influenced the market both inside and outside the European Union as many leading ICT manufacturers employ a policy of having global market access for their products and the EU is a significant market place (Michalek et al, 2004). The EC set out the legislative framework for the regulations that set the performance criteria for different categories of products and are arranged into "Lots". The topic of Eco-design covers numerous environmental impacts including resources. For now, the discussion will focus on “Lot 6” of the Eco-design
legislative framework; the elements that relate to “standby” and automatic shutdown. Other “Lots” are an area for future research, including those that relate to external power supplies and in-use consumption. This is relevant to the research questions as ICT products and services offered to SMEs have been affected by these “Lots”. This demonstrates how wide reaching the influence an EU directive can be and therefore how careful policy makers must be when designing their policies. Policy research that forecasts impacts upon industry before it is implemented in the real world has a great deal of practical usefulness in avoiding economic and social inefficiency. The primary Set 1 research work conducted in this PhD project is useful in demonstrating how agent based modelling can be used to examine the effects of a carbon tax on the ICT market.

Eco-design directives are designed to influence the “in-use” energy efficiency performance; i.e. the energy consumption of the device while being used by the consumer. However, by changing the performance specifications, products had to be redesigned and sometimes different production techniques applied. Therefore, it is possible that “embedded energy” (the energy consumed in manufacture and getting the goods to market) in the new directive compliant products could be greater in the old products, which were designed to be economical to manufacture (Abrahamse et al, 2007). This is largely because the energy consumed in production is an overhead paid for by the manufacturer who has a strong incentive to minimise their energy expenditure, especially in an environment of rising real term energy costs. Therefore, it could be open to debate if the directives had the desired effect of overall reduced environmental impacts. Only after extensive Life Cycle Analysis (LCA) would it be possible to see if the directives have the desired effect (Peng et al, 2016).
2.2.3 Energy Star, Eco-labels and Product Carbon Foot printing

In this section of the thesis there is a brief discussion of eco-labels (labels designed to give an indication of a product or service's environmental impact in one or more parameters) and product carbon footprinting (PCF) (carbon emissions associated with a product or service). The Energy Star eco-label has been in existence for a relatively long time, first appearing in the early 1990’s. It differs from the Eco-Design directives as it is a voluntary scheme and therefore manufacturers choose to enter the scheme. Usually this is when they wish to obtain a sales advantage over rival firms by having an extra differentiator from their competitors and demonstrate their commitment to improving environmental performance. Thereby the eco-label applies a governmental influence without a direct regulation (Jordan et al, 2003). The Energy Star scheme was founded by the US Department of Energy and the US Environmental Protection Agency and covers a wide variety of domestic and commercial goods. For the purposes of this thesis, only the ICT related aspects of the labelling programme are considered.

On the 19th of May 2010, the EU endorsed the use of ecolabels in the Directive 2010/30/EU. This directive should encourage greater use of ecolabel initiatives across the ICT industry. PCF labels are a subset of ecolabels that look at the greenhouse gas emissions associated with the lifecycle of a product or the employment of a service, which is of particular relevance to this thesis.

There is an expanding list of labels dedicated to a subset of LCA focusing solely on the carbon emissions or the carbon dioxide emissions associated with the consumption of products and services. Because of the extensive use of fossil fuels in the production of electricity throughout the industrialised world, the product carbon footprint of a device is related to the amount of energy it consumes in production and usage. Therefore, the topics of PCF and energy efficiency are very closely related. The use of PCF labels may make consumers, indirectly, more aware of the energy efficiency of the products they are buying (Upham et al, 2011). This is another example of how environmental policy could affect a private market, this time done through consumer choice after improved information. Linking this back to policy research and design if firms and government bodies were able to simulate the effects of labelling or carbon foot printing they could determine how best to maximise the outcomes.
The use of eco-labels was not modelled in the Set 1 and Set 2 computer simulations conducted for this PhD project; it was assumed that all products and services would have the same labels therefore nullifying their differentiator effects. Different eco-labels would be an interesting parameter to add in future work.

2.2.4 Energy Security and Solidarity Action Plan

This section discusses the Energy Security and Solidarity Action Plan, a very high level intergovernmental policy that influences the design of national laws, regulations and taxes. Policies designed to improve energy security often overlap with policies designed to improve environmental performance and reduce greenhouse gas emissions. This is often due to the physical link between how energy is used by society and what fuel are consumed, i.e. the continued reliance on fossil fuel imports. The European Commission published the Energy Security and Solidarity Action Plan in 2008 to harmonise the efforts of member states and the different directorate generals (DGs) of the European Union (Umbach, F. 2010). This impetus encouraged nation states such as the United Kingdom to develop policies that guided firms and consumers to a lower carbon and energy consumption pathway. The simulations devised in this thesis give possible pathway progressions for ICT consumption (procurement of “cloud” services versus new hardware) as the Climate Change Levy (CCL) increases, discussed later in the chapter. All other EU directives discussed in this thesis are subordinate to this action plan.

In October 2006, the European Commission announced the Action Plan for Energy Efficiency (Umbach, F. 2010) where it laid out the skeleton for future actions that would lead to policy and regulations of the European Union. This led to the policy objective of a 20% reduction in energy consumption in absolute terms by 2020 in the policy ratified as European Parliament resolution 10-05-2007. This policy plan was itself inspired by policy makers in the EU responding to evidence that anthropogenic greenhouse gas emissions were causing climate change (IPCC, 2007). The close link between electricity production and the use of fossil fuels which emit greenhouse gases meant that energy efficiency gains that reduce electricity demand would in turn reduce the demand for fossil fuels (Umbach, F. 2010). This is a core premise of the Action Plan for Energy Efficiency and this document has steered regulations in the EU Directorate General (DG) for Environment, the DG for Energy and DG Enterprise and Industry. The influence of the action plan can be seen in amendments to Eco-design and later ecolabel framework directives.
Below is a quote directly from the Action Plan for Energy Efficiency, (later renamed Action Plan for Energy Efficiency 2007 – 2011), and demonstrates the wide range of influence the policy was expected to have in the formulation of new regulations and targets across EU activity. The Action Plan came into force from the 1st of January 2007 and extended to the 31st of December 2012.

*Effective action on energy-consuming equipment and appliances requires steps on two fronts: standards for the energy yield of appliances and an appropriate, consumer-focused system to label and evaluate energy performance.*

To this end, the Action Plan provides for the adoption of Eco-Design minimum standards to improve the energy yield of 14 groups of products (including boilers, televisions and light fittings) and to extend it to other products in the long-term. In addition, the Commission hopes to strengthen the rules on labelling, in particular by regularly updating classifications and extending these rules to other equipment.

On the basis of Directive 2006/32/EC on end-use energy efficiency and energy services, the Commission plans to draft guidelines, a code of conduct and a certification procedure applicable to all sectors.


The EU recognised that it would be advantageous to seek out international cooperation on the issues. This is partly since, by creating new energy efficiency regulations, the EU could be putting firms at a competitive disadvantage compared to firms from outside the EU, because of the increased investment costs they would face (Gutowski et al, 2005).

### 2.2.5 Energy Prices

From the 1990s through to 2008 the real cost of energy (considering inflation) rose for three main reasons. (Baumeister and Kilian, 2014). Firstly, the number of people who demand crude oil either directly or indirectly rapidly increased because of the economic development in emerging nations (Schandl *et al*, 2016). Therefore, as consumers own more electronic devices there is a structural increase in the demand for energy across the globe, supporting price rises. Secondly, the US dollar devalued against most other mainstream currencies since 2007. Like many international commodities, crude oil is marketed in USD and when the USD devalues crude oil producers and traders increase their prices to maintain their purchasing power (Askari, and Krichene, 2010). Even though there has been recently a relative oversupply in crude oil suppressing spot
prices the preceding years of higher prices have already stimulated the market to become more energy efficient as consumers attempted to reduce overheads. And finally, there are the influences that speculative trading has on pricing. This can increase the volatility of energy prices further increasing the concerns policy makers have over energy security (Kaufmann and Ullman, 2009). Indeed, the EU is using programmes related to improving energy efficiency and migrating to a low carbon economy to improve energy security – as discussed earlier in this chapter.

As mentioned earlier, energy prices over the last 20 years have risen significantly. According to the UK’s Department of Energy and Climate Change (DECC) Energy Prices Report December 2010, the price of natural gas increased 102% in real terms between 1998 and 2008. Gas prices are important indicators of energy prices in Europe because of the high proportion of electricity produced using gas-fired power stations. In the long term fossil fuel and energy prices tend to rise and fall with a high correlation with one another (Regnier, E. 2007). These fossil fuel price rises have altered market conditions and the way consumers make their purchasing decisions, encouraging the purchase of technologies that improve the energy efficiency performance of systems (Marik et al, 2008). Also, higher energy costs have increased the operating costs of ICT equipment and this in turn is likely to alter the procurement decisions of actors purchasing ICT products and services to favour options with lower in-use energy consumption (Brzeskot and Haupt, 2013). This is relevant to this thesis as rising energy prices influence behaviour and ICT industry, because of additional decision factors such as reliability and functionality, behaves differently to many consumer markets and makes it academically interesting to examine. This was done in the Set 2 models discussed in Chapters 5 and 6.

2.2.6 Green Procurement

Government sector procurement in the European Union is worth approximately €2 trillion a year, or around 17% of the EU’s GDP (Amann et al, 2014). ICT firms cannot afford to ignore the government market as they are potentially a significant source of revenue to them. Therefore, the environmental performance of products and services can become a differentiator as government procurement often requires energy consumption as a factor in decision-making process.

Within the European Union there is a core directive for public procurement; “2004/18/EC Public works contracts, public supply contracts. This applies to
government procurement. The most significant amendment to the directive for public procurement is related to the clarification of rules on purchasing ICT equipment and specifying performance criteria rather than commercial labels. The clarification was a response to the EU policy objectives stated in the Action Plan for Energy Efficiency 2006. It is not permitted for government bodies to specify eco-labels for the products they buy. They must instead specify the individual performance indicators individually (for example standby consumption in watts) for each parameter and product or service. It is, however, permitted that the criteria used are copies of the performance criteria used to generate the ecolabels. Also, the government bodies must make sure that there is no preferential treatment for domestic suppliers.

There has been a growing shift amongst procurement professionals towards "best value" or "total cost of ownership" procurement specifications rather than focusing on initial "sticker" price. Here the focus for the procurement team is to secure the lowest overall cost of ownership, rather than simply signing the contract with the lowest upfront costs (Ritsma et al, 2009). This has been seen in both public and private sector procurement. With the rising cost of energy, devices with lower consumption often have the competitive edge, especially with items like servers where the in-use energy consumption can exceed 90% of the energy associated with the life cycle of a server (Whitehead et al, 2015). This is likely to alter the composition of products and services sold as procurement teams alter tenders to place a greater emphasis on in-use energy consumption. This section is of great significance to this thesis as ICT Managers' preferences are likely to be influenced by these concerns for total value. This was mentioned frequently during the interviews with ICT Managers conducted during the preliminary research phase preparing the background information needed for developing the computer simulations.

The quote below is taken from europa.eu and summaries the EU's position on the Green Public Procurement (GPP). The Directive states that, in concluding public contracts, public authorities:

"shall endeavour to procure only such products which comply with the criteria of having the highest performance levels and belonging to the highest energy efficiency class.” [http://ec.europa.eu/environment/gpp/index_en.htm].

Member States are also empowered to set minimum criteria for the procurement of energy-related products. The recast Energy Labelling Directive extends the scope of the
energy labelling regime and establishes new efficiency classes for the most energy-efficient products.

The use of “green procurement” (a phrase used to define procurement tenders where environmental performance is the highest or one of the top criteria for winning the contract), including criteria for energy efficiency performance, can often help to achieve wider management objectives of organisational efficiency and expenditure (van Asselt et al, 2006). This is an additional incentive for decision-makers to adopt green procurement beyond the original policy objectives. There are a number of voluntary initiatives available to both public and private sector procurement professionals to assist them in seeking out best practice in green procurement. This programme for green procurement helped to inspire the final research questions – how much can a market be encouraged to change using taxes before the use of strict regulations are necessary to meet government targets on GHG emissions?

Many large firms mirror the procurement policies of governments (Kang et al, 2005). This can be for several reasons: they look to government for best practice and they have committed to an environmental management protocol such as ISO 14000 series or EMAS (Eco-Management and Audit Scheme) that encourage strong procurement policies and supply chain monitoring. Multinational corporations are often keen to show that they are good corporate citizens and applying recognisable environmental management standards such as ISO 14000 series and EMAS to their supply chain helps to demonstrate this (Reynolds and Yuthas, 2008). Again, this can influence the preferences of ICT procurement decision-makers and therefore was considered during the development of the research computer simulations.

A factor that may be limiting change in private sector procurement is the design of “key performance indicators” (KPIs) for procurement teams; the criteria by which they are awarded pay bonuses. Within the private sector, it is frequently the case that often bonuses are set against the discounts the procurement team deliver against the initial price of the contract. It is relatively rare when a bonus is linked to the saving associated to the total cost of ownership (Degraeve et al, 2005). It is only in firms where the procurement director has redesigned the bonus structure to take total cost of ownership into account that devices with better energy efficiency performance rather than a relatively low purchase develop a competitive edge.
2.2.7 Climate Change Levy (CCL)

From the 1st April 2011, the UK government announced that they were to introduce a carbon tax on non-domestic uses of energy, the tax is an extension to the Climate Change Levy (CCL) (originally introduced for large emitters in 2001 (Varma, A. 2003)) and was to be applied to the consumption of electricity, gas, liquefied petroleum gas (LPG) and solid fuels. The financial impact on business was to be offset, at least in principle, by a reduction in the level of National Insurance employers would pay for each employee (reducing from 12.2% to 11.9%). An example of a policy designed to reduce environmental impacts without having an adverse effect on the economy. This is in keeping with the United Nations Environmental Programme (UNEP) descriptions of ideal environmental policy discussed earlier in this thesis.

In 2005, the UK government reported that the CCL was expected to reduce UK carbon dioxide emissions by 12.8 million tonnes per year by 2010. In addition to the CCL the government runs a scheme called Climate Change Agreements (CCA) where private sector entities agree to have their environmental impacts assessed and benchmarked. These entities then commit to reducing their emissions, energy consumption and resource consumption and they then receive significant discounts (up to 90%) on the CCL (Barker et al, 2007). According to the forecast from 2005 the UK government anticipated that around 20 million tonnes of carbon dioxide emissions would be reduced by combined influences of the CCL and CCA. That is equivalent to around one third of the total carbon emissions reduction UK government policy was expected to achieve by 2010, it is as yet unreported how much of this was achieved.

The principle research question of this thesis was inspired by the CCL partly due to its relative simplicity when compared to the EU emissions trading scheme (EU ETS) and partly due to the academic and commercial usefulness in examining the potential market impacts. The techniques learnt from this examination (in using agent-based models) could be applied to other policies in future research work.

2.2.8 EU Emissions Trading Scheme

The European Union Emissions Trading Scheme (EU ETS) places a legal limit on the carbon dioxide emitted by business and creates a market and price for carbon allowances. The trade in these allowances, also known as permits, incentivises scheme
members to become more energy efficient, as they can sell unused permits to improve their profitability. Conversely, if they are inefficient they have to purchase permits from the market, thereby risking giving their competitors an advantage by taking on higher overheads. The scheme covers 45% of EU emissions, including energy intensive sectors and approximately 12,000 installations (Ellerman and Buchner, 2007). This thesis is mainly focused upon the small to medium enterprise (SME) sector, who are relatively more intensive users of ICT. There is less of a need to focus research efforts on the EU ETS at this time. However, it would be of interest to apply the ABM research techniques to the EU ETS in further research.

The Department for Energy and Climate Change (DECC) in the UK introduced opt-out provisions for the EU ETS for smaller emitters and hospitals, allowing them to reduce their GHG emissions with lower administration costs. One of these opt out options was the provision of CCAs. These provisions are expected to deliver an equivalent carbon reduction to what would have been seen under the EU ETS scheme had these entities been part of it.

### 2.2.9 Contraction and Convergence

A common principle in academic research into sustainability issues facing society is the principle of “Contraction and Convergence”. This is where people living in developed economies consume fewer resources, emit less pollution and greenhouse gases. Conversely, people living in developing countries are allowed to “catch up” with their resource consumption. However, while contraction and convergence is a popular idea with an environmentally minded minority, mainstream politicians have been uneasy in suggesting contraction and convergence as policy either at governmental or intergovernmental levels (Kuntsi-Reunanen and Luukkanen, 2006). This is partly because the main mantra of modern western politics would appear to be “better living through growth” and partly because much of economic prosperity is measured through consumption. New indexes that attempt to measure a “happiness” quotient could be a partial solution, these often result in league table where nations are dramatically reordered when compared to those based solely on GDP or GDP per capita (Hayo and Seifert, 2003). This is relevant to the research questions in this thesis as the principle of contraction and convergence may influence preferences of ICT decision makers and policy designers responsible for carbon taxes.
An alternative principle to using “contraction and convergence” as a motive to introduce policy is that of resource efficiency for greater security. Security of supply for energy and other vital resources (such as iron ore, grain, crude oil, etc.) is critical for a modern economy to function and achieve growth. As described by the Stern report (discussed later in this chapter) and beyond, there are opportunities for greater resource efficiency than allow for significant real economic gains, for example energy efficiency in heating homes and offices, furnaces, use of renewable energy, reuse of aggregates. The environmental policies described in this chapter are intended to increase energy efficiency, but not to reduce economic output, and therefore reduce the EU’s reliance on energy imports – a source of political uncertainty and risk to the economy.

2.3 Policy Environment

Section 2.3 reviews how governments aspire to use policy, including the EU and UK policies described in section 2.2, to regulate the commercial market to achieve goals for environmental performance. It also includes a review of free market influences.

2.3.1 Design of Environmental Policy

The design of an environmental policy depends upon the goals it is set out to achieve. In turn these goals are dependent upon the political imperatives of the policy makers and enforcement bodies. The stylised graph in Figure 2.1 represents the desired outcomes of good environmental policy design as described by Smith et al, (2010). They described how good environmental policy encourages society to decouple economic activity from resource use (such as fossil fuels, wood, metals, etc.). This is usually as a result of improved efficiency in usage, reuse of goods, recycling of materials and changes in business models – for example, the use of leasing a service rather purchasing a product; thereby allowing multiple users to achieve their goals with less physical hardware. For example, bicycle rental schemes result in fewer bicycles meeting the transportation needs of a number of people who would otherwise need a bicycle each. The utilisation rates of the bicycles in the schemes is greater than in typical ownership. Hence bicycle rental schemes reduces the resources required by society to meet its transportation needs (Boquet, Y, 2010).

In the UNEP report of 2011 the authors describe how they believe the best environmental policy should have multiple effects and not impact negatively on human wellbeing. Indeed, there is ideally a positive impact on human wellbeing because of the
improvement of the environment that society inhabits. For example, a policy to remEDIATE quarries into ponds or nature reserves brings about positive legacies (UNEP, 2011). The UNEP group also strongly imply that well designed environmental policies would not adversely affect economic activity. This is important as most governments wish to increase GDP with the belief that there is an associated improvement in human wellbeing (Brady et al, 2007). Critical to the aim of continuously increasing economic activity and simultaneously reducing environmental impacts is reducing society’s need for natural resources. This may either be through increased resource efficiency, reuse, recycling or changing products and services so that they are more sustainable in the first place (Bithas and Kalimeris, 2013). In Figure 2.1 there is a schematic diagram demonstrating the desired direction of travel over time for these factors and the desire to decouple human wellbeing and the economy from intensive resource use. This was famously highlighted in the 2006 Stern report to the UK government (Stern et al, 2007). In this report, the Stern group of authors pointed out that here were opportunities to develop new industries, such as a renewable energy sector or machine leasing, while becoming environmentally more efficient (most notably in the renewable energy sector).

*Figure 2.1: An idealised view of how environmental policy should be designed. Source the United Nations Environment Programme 2011, schematic diagram author’s own.*
2.3.2 Free Trade and Globalisation

This section is designed to help give context to the research question. A key aspect of the modern world economy is the principle of free trade between nations, whether this is the sale of finished goods, services, energy or raw materials. The ICT market is a significant player in the global economy, both as a primary industry and as a facilitator of economic activity in almost every other industry and the technology utilised is almost homogenous across the globe (Desruelle and Stancik, 2014). Many governments of the world’s nation states adhere to principles of the “Washington Consensus” (Onis, 2005), with “free trade” being the most important principle to this thesis. This model for running free market capitalism has been widely adopted for over 40 years and has led to numerous structural changes in national and international economies known collectively as “globalisation” (Tisdell, 2001). The International Monetary Fund (IMF), the World Trade Organisation (WTO) and the World Bank were all borne out of the political accords created by governments following the principles of the Washington Consensus. The focus was on free trade amongst nations and as a result there are a number of large multinational ICT conglomerates that are able to operate in multiple international markets because of these free trade agreements and regulatory bodies (Williams et al, 2011). Therefore, environmental policy that affects the ICT industry in the EU, a large key market for most multinational ICT firms, would likely impact upon all their markets as, due to economies of scale, most firms make their hardware as universal as possible (often only power supply units change) (Choung et al, 2012). To a lesser extent the same is also true of an environmental policy applied in the UK market place.

In this section of the thesis issues of globalised trade and supply chains are examined under the lens of their compatibility, or for that matter incompatibility, with the principles of sustainable development. This is relevant to the research question because carbon taxes are often used by governments to encourage firms and individuals to behave in a more “sustainable” manner than their previous “business as usual” economic model (Sanden and Azar, 2005). Regarding the research question many of the principle players in the UK ICT industry are large multinationals who operate in multiple markets with very similar hardware and services being offered universally (often it is only the power supply units and languages of instruction manuals that change) (Brueller et al, 2015). Therefore, when there are environmental policies in the
EU or the USA that affect the performance criteria of the ICT hardware they are likely to affect the product sold throughout the world (Tobias and Pongratz, 2004). Often ICT lobby groups try to engage with policy makers and get them to adopt performance criteria based on international third party labels. A prime example was the EnergyStar labelling system (Hong et al, 2014) that ICT4EE (the industry lobby group for ICT industry that lobbied the EU and EC on matter regarding energy efficiency) successfully pushed into the EU market after its adoption in the US. There is a direct link between the objectives of sustainability, improved energy efficiency and carbon taxes (Ayres et al, 2007) as ICT firms seek to maintain market access and competitiveness and governments seek to impose carbon taxes and other measures to improve environmental performance. For societies to become more sustainable they have to become more energy efficient and carbon taxes are a policy instrument used by governments to encourage this process (Fischer and Newell, 2007).

2.3.3 Free Trade and World Trade Organisation

Most of the world's nation states participate in cross border trade. This occurs for several reasons – whether it is to access hard currencies, drive economic growth, increase consumer choice or influence world affairs. In relation to this thesis the most important issue is the use of trade as a driver of growth (Tisdell, 2001). China opened its borders to trade in the 1970s and this has been instrumental to its impressive economic growth ever since (Wang, 2003). There they also used trade in goods to gain hard currency for the purchase of resources (e.g. US dollars for the purchase of iron ore or crude oil) and to access better technology (Saggi, K. 2002). Brazil, and more recently, India are also following similar growth paths as China and are part of the fast-growing emerging nations colloquially known as BRICS (Brazil, Russia, India, China and South Africa). Development of trade also allows for growth as firms gain new markets to trade into and expand their customer bases. Large multinational ICT firms such as HP, Dell, Oracle, Apple and SAP are dependent on being able to operate in numerous large markets to achieve their high market values. Therefore, the WTO and the EU are important organisations to these multinational ICT firms as they maintain free trade across nation state boundaries (Rangan and Sengul, 2009).

The WTO is the successor to the General Agreement on Tariffs and Trade (GATT), and is the organisation used by member states to arbitrate in trade disagreements. However, it did not have sustainable development as a core functional criteria and this has arguably helped to reinforce the "business as usual" approach to world trade (Tarasofsky and
Palmer, 2006). The “Doha Round” of trade talks did much to change the agenda putting the onus of environmental protection onto developed countries, in particular with respect to climate change. The Doha Round made it easier for industrialised nations to purchase “carbon credits” from developing nations. This most likely occurred because of cooperation amongst many of the poorer nations to use these purchases to gain leverage against traditionally more powerful trading nations. There could therefore be a change of emphasis in the near future with environmental protection becoming a key aspect of the work of the WTO (Bellmann et al, 2011). This reinforces the use of carbon taxes by governments in developed countries keen to make their industries more efficient and better able to compete with firms from emerging countries which have an excess of carbon credits.

### 2.3.4 Subsidies and Tariffs Skewing Markets

There is an expectation in neoclassical economic theory that the principle of free trade will lead to an efficient allocation of resources through the price mechanism and that the economy of a society adapts to meet these allocations (Smith and Foley, 2008). Government policies affect large scale economies in a variety of sectors. Here the example of agriculture is examined, partly because it has been examined by numerous academic research groups and the mechanisms in which policies affect the industry are assumed to be similar to how policies would affect the ICT industry. There is a long history of state intervention in the agricultural sector in most western nations and farmers have often adapted their business models to best fit with policies and subsidies (Lien and Hardaker, 2001).

However, in reality, there are often barriers to free trade which lead to what are called “market failures” (Tamalia and Charlebois, 2007). In the ICT market place, there have been accusations of governments building unfair barriers to trade or seeking unfair advantage through anti-competitive behaviour. Examples of this are the import duties in South Korea on foreign made ICT hardware (Siles-Brugge, G. 2011) and the banning of Blackberry hardware in some countries due to the use of encryption software.

Arguably one of the greatest market failures in the modern world revolves around international agriculture (even considering the recent crisis in the world’s financial systems). The skewed markets caused by large agricultural subsidies and associated “dumping” by the developed and developing nations have been cited to cause hardship for countless millions of the world’s poor (van Meijl and van Tongeren, 2002).
Examining the agricultural industry in this literature review is relevant to the overall thesis as the market in agriculture is assumed to operate fundamentally in the same way as the ICT market place and therefore lessons learnt there can be applied to the ICT industry. Because of the highly political nature of agricultural policy it is a sector that has been closely researched by a significant number of economists and therefore there is much high quality academic material that can be cited. The common agricultural policy in the EU and the payments made by the US Department of Agriculture are the two examples of subsidy programmes. There are also subsidy programmes in emerging nations such as China and India (Robinson, W.I. 2015). The ICT industry has also been skewed by subsidies, using “soft loans” and barriers to trade, these have also led to market inefficiencies in markets (Mahyideen J, 2012). It can be argued that carbon taxes would lead to more energy efficient hardware being favoured in the markets with the taxes. Some ICT firms have argued that carbon taxes and other environmental regulations lead to diminished consumer choice and favouritism (Bechtel, et al, 2012).

Subsidies have been controversial for years and the political weight behind keeping them has to be strong. Farmers tend to have a good image at home and the belief that nations must be able to feed themselves is a powerful argument. Within the EU for example it is unlikely that such a large farming industry would be able to exist without the subsidies that it receives and concerned parties are good at protecting their interests (Bernard, et al 2006). The reason these subsidies are considered as controversial is that there is strong evidence that they skew the world’s food markets, as surpluses enter the world export market artificially cheaper than they would have been if left to the free market (Anderson, et al 2006). These surpluses entering the world export markets have been known to crowd out domestic supplies in developing countries. In extreme cases, it has put farmers in poor nations out of business as the subsidised food supplied from developed nations enter the market cheaper than the locally produced foods (Anderson, et al 2006).

Similar scenarios have occurred in the ICT market where Japanese printer manufacturers were accused of selling hardware into the international market cheaper than it cost them to produce the goods. This meant that they could undercut rivals and force them out of the market. This practice became known as “dumping”. Dumping results in a market failure analogous to that in agriculture where local producers are forced out business due to cheap imports. It would be interesting future research to use Agent Based Models to simulate the effects of reduced subsidies in Developed nations –
this is discussed in chapter 6 of this thesis. There is a concern of “dumping” by companies from, for example, Japan and China in the technology marketplace, for example the manufacture of motherboards, mobile phones and peripheral componentry (for example with office printers in the 1970s and 1980s) at a below cost basis, resulting in factories in western countries closing due to them becoming uneconomic to run competitively (Bernhofen, 1995). Often policies designed for environmental protection are suspected to be designed to protect domestic suppliers. Therefore, when the EU or the UK design their environmental policies they are careful to make sure specifications are not anti-competitive. The Eco-Design directive, detailed later in the literature review, does not directly use commercial labels in its performance descriptions to help avoid accusations of favouritism (Grote et al, 2007). To counter the effect of dumping numerous nations have applied import tariffs in order to protect domestic production from imports. These import tariffs have been an obstacle to agreement to the Doha Round of trade talks at the World Trade Organisation (Anderson and Martin, 2007). It is difficult to judge the equity of the situation. It can be argued that import tariffs are a necessary response to prevent further hardship to domestic manufacturers. However, they could potentially further skew markets, encourage trade wars and negate some of the probable advantages brought about by free trade and comparative advantage (Felbermayr et al, 2013). This is relevant to the research in this thesis as most of the ICT hardware consumed in the UK is designed and manufactured overseas and the government is acutely aware that the designs of its policies must not be construed as protectionism.

2.3.5 Climate Change Abatement

This section provides a brief and broad overview of differing solutions to climate change and how it relates to the ICT industry and policy design. Assuming that climate change is regarded as a serious issue for governments to abate and that sustainability policy is a linked objective to climate change abatement. There are a multitude of options available to reduce climate change. These range from policies designed to alter consumer and manufacturer behaviour, all the way through to “geoengineering” to physically counter the effects of climate change.

The first option to be discussed is policy instruments designed to alter consumer behaviour and the market (Fell and Morgenstern 2010). Policy instruments can vary from taxes on consumption (Shittu and Baker 2010), for example the Climate Change Levy (CCL) a carbon tax in the UK, to grants to stimulate new areas of the market. This
stimulation can be through the invention of new products and services, like those used to promote the purchase of electric vehicles. Some NGO’s favour policies that promote a principle known as contraction and convergence, this is where modern consumer societies such as the UK and emerging economies such as Angola aim to reach parity in the amount of CO₂ emissions emitted per capita (den Elzen et al, 2008). This concept has a lot of appeal in its simple logic, and it appeals on equality. However, if it were to achieve widespread acceptance it could inadvertently reward nations with rapidly growing populations and even possibly promote nations having high population growth. Human population growth is a key cause of environmental stress (Vorosmarty et al, 2000) and it is unlikely that governments, particularly in developed countries with slowly growing populations, will be willing to promote policies that could encourage booming populations in other nations. Ultimately, the desire for contraction and convergence applies a pressure on society to become more energy efficient and consume fewer fossil fuels on a primary basis. ICT firms are integral to this pathway as they are often able to apply technologies that make society more energy efficient (Hischier and Wager, 2015).

Reforestation as a government policy is not often enacted despite its simplicity; trees act as carbon sinks and deforestation is an accepted contributor to both climate change and biodiversity loss (Sasaki and Putz 2009). It has been estimated that around 15% of the world’s anthropogenic CO₂ emissions are caused by deforestation (Boyd, W. 2010). Therefore, there is a strong impetus to examine policies that could reverse this damage. A future area for research could be using agent based modeling techniques to examine this issue in a similar way to the examination of the effects of carbon tax. ICT firms often use reforestation programmes as an opportunity to offset their GHG emissions (House et al, 2002). It has even been suggested that developed nations pay poorer nations to maintain and even expand their forests through the United Nations Clean Development Mechanism (CDM) (Paquette et al, 2009). This operates in a similar way to the previously discussed carbon credits. This has led to an industry known as carbon offsetting. The principle is that GHG emissions produced by manufacturers and consumers in the developed world can be offset by carbon sinks (such as those produced by reforestation) (Zorner et al, 2008). ICT firms could reduce their headline GHG emissions using carbon offsetting and reforestation. Reforestation is sometimes applied in the analysis conducted to produce the carbon footprint of a product or service, depending on the scope and protocol applied. Product carbon foot printing is discussed further later in this literature review. Currently there is no legal requirement
for ICT manufacturers to support reforestation. However, the use of tradable carbon permits for heavy industry in the European Union’s Emissions Trading Scheme (ETS) is starting to develop a market for offsets and the likelihood is that over time the number of firms and manufacturers that are applicable to the scheme is very likely to expand to ICT firms. A sufficiently robust accounting mechanism and a high enough market value of carbon would be prerequisites of a successful programme (Olschewski and Benitez, 2005).

Energy policies designed to promote low and non-carbon based technologies are commonly used in modern economies as a way of reducing CO₂ emissions (van der Zwaan et al, 2002). Examples include the renewable obligations certificates (ROCs) programme in the UK or the German feed in tariff. These policies usually are designed to stimulate market forces rather than command activity. In Germany, there have been examples of command polices, for example it is a planning requirement that all new coal power stations must be “Carbon Capture and Storage Ready” in order to be considered for planning approval (Viebahn et al, 2008). In the UK, thermal efficiency targets for buildings also are being strengthened and standards are more assertively enforced (Lomas, K. J. 2009). While not directly related to the ICT industry these policies signal that there is a political will to improve energy efficiency and reduce greenhouse gas emissions. Overall, western governments tend to prefer policies that use incentives or encourage voluntary agreements as they then can avoid the costs of enforcement and employ the ingenuity of business - by providing opportunities for profit or competitive advantage (Jaffe et al, 2004).

Economists often use the example of copper for the action of price mechanisms encouraging recycling. During the 1970’s the price of copper rose sharply, increasing the proportion of the metal in the market place that was recycled. It also had the effect of making previously uneconomic seams of copper ore worth extracting and led to an increase in the number of active copper mines (Sverdrup et al, 2014). The price mechanism did succeed in making society more efficient in its use of copper. This points the way to a possible solution to making non-renewable resources used more sustainably by society. For example, the use of a carbon tax on fossil fuels to encourage more efficient use of electricity. If the price of a good truly reflected its non-renewable nature we are likely to see greater attempts to conserve the resources that make up the good (Binswanger, H. C. 1998). It can also be anticipated that the increase in price of these non-renewable resources will encourage consumers to plan their usage more carefully, possibly increasing the amount used for long term capital. For example, fuels
could be used more readily to power machinery that resulted in long term capital investment (for example high value buildings or land remediation), rather than uses that could be regarded as more trivial (for example motorsport). This would also have the side benefit of reducing the flow greenhouse gases into the atmosphere as well as the conservation of fossil fuels.

### 2.4 Transitioning to a Low Carbon Economy

Here the national strategy options available to policy makers wishing to move the society they operate in to a low carbon economy are discussed, building on the policies discussed in section 2.2 and 2.3. This is relevant to the research question as the use of carbon taxes to reduce fossil fuel consumption is a direct result of the policy objective to transition the economy to a low carbon one. It also relates to the ICT industry in a wider sense as the industry is seen as a provider of solutions for achieving a low carbon economy – through teleconferencing, smart metering, energy management, smart traffic management and public transport management etc. Stakeholders who influence decision making are also discussed in detail.

#### 2.4.1 Policy Objectives

There are often several different policy objectives that policy makers wish to achieve, some of these are complimentary to one another while others are contrary. For example, the policy aims of being energy independent and promoting a low carbon energy supply can complement each other if the country in question is looking to achieve its energy independence through the use of renewable energy sources such as wind or wave (Chen et al, 2010). However, there are situations, such as building extra capacity at a major airport, that demonstrate a direct conflict between different policy objectives, e.g. the desire for economic expansion versus reduced GHG emissions. In this case, wish of policy makers to assist an increase economic activity is in direct opposition to the desire to reduce the GHG emissions and improve air quality (Agusdinata and Delaurentis, 2011). However, with respect to the ICT industry the objectives to reduce societal GHG emissions complement the objectives to make ICT equipment and services more energy efficient. Later in the literature review there is an examination the EU directives designed to make the ICT industry more energy efficient and hence reduce its associated GHG emissions (Aebischer and Hilty, 2015).
In most developed countries, there has been a greater emphasis placed by policy makers on the reduction of GHG emissions compared to most developing countries where the focus was on growing their economies (Bowen and Hepburn, 2014). However, this situation is changing and developing nations are now often seen to be tightening their policy stances on greenhouse gas emissions (Oh and Chua, 2010), therefore widening the marketplace for more energy efficient ICT hardware and services to beyond that of the USA and the EU.

Energy security is an integral part of economic development of a nation. It is also important that the energy is cheap enough to encourage growth. At present fossil fuels are still considered by many developing nations as the most cost effective way to achieve a reliable energy supply that is inexpensive at the point of use (Streimikiene and Sivickas, 2008). However due to their associated emission of GHGs from the use of fossil fuels there is a strong pressure within developed economies to find alternative energy sources and improve energy efficiency (Jones and Eiser, 2009). The use of ICT products and services is associated with these objectives both in their in-use phase and in their manufacture (Salahuddin and Alam, 2016). Product carbon footprinting, discussed later in this literature review, is designed to encourage consumers to select products with less environmental impact. The use of ICT products and services is also highly relevant to the wider economy as the clear majority of economic agents use ICT in their work practices and therefore efficiency gains at the point of use have a knock-on effect in the wider economy (Salahuddin and Alam, 2015). In the research phase of the thesis the carbon tax is directly analogous to the UK's Climate Change Levy. This carbon tax is applied to a set of simulations to observe how it changes the purchasing behaviour of SMEs (a key customer demographic of ICT firms) and links the influence of policy to market changes.

However, arguably the most important pairing of policy objectives is the combined objective of improved well-being in society, as opposed to solely targeting economic growth, with that of improving environmental performance (including the goal of reduced greenhouse gas emissions) (D’Acci and Lombardi, 2010).

In the Set 1 and Set 2 models developed in the research phase of this thesis there is an attempt to observe the link between carbon taxes (a common environmental policy) and the ICT market through agent based model simulation. In this, the policy makers are looking to reduce the GHG emissions of the ICT industry by encouraging migration from
more energy intensive technologies (hardware) to lower energy intensive technologies ("cloud" solutions). In the models carbon taxes are complimentary to the ambition to produce a low carbon economy.

2.4.2 Stakeholders and Engagement

The term stakeholder engagement is commonly used in the language of policy makers (Cocklin et al, 2007). According the Webster’s dictionary the term stakeholder can be defined as “one who is involved in or affected by an action”. Using this definition means that there are a broad range of stakeholders whose interests must be accounted for during a stakeholder engagement process when setting policies designed to assist society's transition to a low carbon economy, due to the pervasive use of energy throughout the economy (Barker, 2002). This concept of a stakeholder was vital to this PhD project with the selection of industry professionals as a key set stakeholders to interview and develop an insight into the behaviour of the ICT market. The software agents in computer simulations in the research modeling phase represent the various key stakeholders within the ICT industry. With respect to energy consumption the ICT industry is incorporated in a number of ways, as a primary consumer of energy in manufacturing and distribution, in the in-use phase at customer premises and in the recycling, end-of-life and reuse phase of hardware. It is important for policy makers to adjust the balance of policy objectives to compromise amongst the stakeholders and maximise societal utility (Lindahl and Soderqvist, 2004). However, in western democracies there is also the imperative to achieve results that please voters and improve the chances for re-election for governments (Fredriksson et al, 2013). It can be argued that the desire to achieve results within an election cycle time line leads to suboptimal policy design.

To ensure that the models developed in this thesis accurately reflected real life scenarios and influences on SMEs an overview of the differing stakeholder groups follows, including how they relate to one another in policies that promote a transition to a low carbon economy and how they are incorporated (or not) into the models.

2.4.2.1 The General Public

Members of the general public constitute the largest stakeholder group whilst arguably being the most difficult to maintain a consistent relationship with for policy makers
The state of the economy and awareness of environmental issues are subject to temporal change. Applying the principle of the Environmental Kuznets Curve, when the willingness of a society to pay for environmental improvements increases as the wealth increases (Dietz and Adger, 2003), to that of policy making, can lead to changing results depending upon whether the general public are experiencing economic recession or growth. When in recession the general public are more likely to resist policies that will increase their cost of living, even if there is an environmental benefit such as reducing the dependence on fossil fuels and encouraging a low carbon economy (Aggarwal, P.K. 2008). This is directly relevant to the research questions raised by this thesis. The period of economic growth during the 1990s and 2000s and increased awareness of societal impacts on the earth’s ecosystem and led to greater voter demand for environmental protection. (Ruedig, W. 2012). Overall, the general public was ignored by the computer Set 1 and Set 2 simulations in the research phase as they are not directly relevant to the decision making process of SMEs selecting ICT solutions.

### 2.4.2.2 Private Sector Investment

Using the model of investment banking as an example of private sector investment, the decision makers at the banks (the stakeholders) have a duty of care to their shareholders to achieve maximum shareholder value. Currently, this is usually defined as maximising profits (Elhauge, 2005). Bankers have the entire spectrum of investment options available to them, including investing in projects that would lead to a low carbon economy. Unless there is an additional incentive to invest placed by government policy, such as tax breaks, banks evaluate their decision to invest into a project based upon normal commercial criteria such as investment yield and return on investment (Fiordelisi and Molyneux, 2010). The main exception to this rule is when the bank has been mandated in its charter to seek out investments that improve the carbon footprint of society (Sarokin and Schulkin, 1993). Often banks or investment funds with such a charter are known as Socially Responsible Investment (SRI) or Green funds (Cumming and Johan, 2007). There is an argument that as these funds tend to invest into projects that are low carbon, as fossil prices rise, the performance of these investments should improve as they gain a competitive advantage over funds and banks that had more short-term profit maximising objectives (Harmes, 2011). This can be relevant to SMEs looking for loans from banks and or investment funds, the ICT usage of the SME is often used as a factor in judging the overall environmental performance of the firm (Schaeffer,
G.J. 2015). This can provide an extra parameter for SMEs deciding between updating their physical hardware packages or opting for a "cloud" based service which is more energy efficient.

Therefore, taxes and incentives are a significant lever for change that government policy makers could pull if they were to use taxes and incentives to encourage private investment into projects that encourage a low carbon economy (Zylicz, 1999). These investments could be in SMEs similar to those modelled in this PhD project. Significantly, this would include alternative low carbon energy supply projects, ICT capital investment or transportation schemes (Newcomer et al, 2008).

2.4.2.3 Government Investment

In many nations (for example Norway and Qatar) the government is a significant source of investment capital funding and often use investment as a means to enhance the effectiveness of their policy programmes (Pfeifer and Sullivan, 2008). These investments are often “loss leading”, designed to stimulate private sector demand at a later stage (Kong and Kwok, 2007). For example, it could be feasible that after research and cost benefit analysis that a government such as the UK's decide to provide grants to SMEs to help them to upgrade to more energy efficient ICT equipment and services, thereby reducing the country's overall GHG emissions and helping the government to achieve its vision 2020 aims.

Government investment was not included in the models in this thesis as the models focus on private sector SME’s and currently no governmental grants are available for ICT upgrades, so in this respect the models reflect real life.

2.4.2.4 Government Policy Makers

In designing policy, government policy makers have to make decisions on how to balance the requirements of different stakeholders in society in order to achieve the optimum result (Grudens-Schuck, 2000). How this optimum balance is defined in a democracy is up to politicians to contest, the electorate to vote for and the government to implement once given a mandate (Joshi, 2010). While policy makers were not modelled directly in the Set 2 simulations the outcomes and the observed emergent behaviour of the agents in the ICT market place would be of interest and could help the policy makers set carbon tax policy or pricing levels to achieve their desired results.
2.4.2.5 Industrial users

Heavy industrial users of electricity are a significant stakeholder group in the debate of how to manage a transition to a low carbon economy. Often these heavy users, such as aluminium smelters, are significant contributors either directly or indirectly to a nation’s GDP and as such the trade-off between economic activity and environmental protection is particularly difficult (Rauch, J. N. 2009). Without access to a large low carbon supply of energy, a reduction in greenhouse gas emissions would most likely be associated with a reduction in output. This is the reason Russia requested its targets for the Kyoto Protocol was based upon their pre-recession economic output, rather than the output seen during their recession of the early 1990s (Hammons, T. J. 2006). While heavy industrial users were not included in the creation of the computer Set 1 and Set 2 simulations in this thesis, they could be a valuable additional parameter in future work as they are heavy influencers in both the capacity and cost of a country’s energy supply.

2.4.2.6 Energy Utilities

The firms that provide society’s energy are critical stakeholders in the transition to a low carbon economy. They consume fuels in a number of forms in order to generate electricity to provide the capacity to do work. This is vital for an economy to function, through the use of electricity to power factories, railways, homes, etc. Therefore, by fundamentally changing the way in which electricity is provided to users to a low or non-carbon format, significant improvements in the GHG emissions can be achieved (Hardisty, et al, 2007). It is estimated that in the United Kingdom around 30% of the nation’s greenhouse gas emissions are associated with the production and transmission of electricity (Baiocchi and Minx, 2010). In a similar way, as industrial user stakeholders were excluded from the simulations energy utilities were also excluded, however they could prove to an interesting addition in future work as they are often the first part of the market affected by carbon taxes like the climate change levy.

2.4.2.7 Transport

Transportation in a society is usually a heavy consumer of fossil fuels and using the UK as an example around 25% to 30% of the nation’s greenhouse gas emissions are produced by the transport sector (Kwon, T. H. 2005). Like the energy sector, adapting the transport sector to function on low or non-carbon fuel sources would greatly enhance society’s transition to a low carbon economy. Again, transport as a stakeholder
was not included in the simulations as transport is not a direct component in decision-making process for selecting between ICT options.

2.4.2.8 Local residents

It is common for pockets of local residents near power stations or transport links, particularly airports, to be vocal in their anxiety to a change in their local environment. Grassroots protests amongst residency groups have led to planning authority U-turns. For example, the plans for the building of terminal five at London Heathrow Airport were placed into a state of hibernation due to the well organised local residency group successfully raising the issue to a national debate about greenhouse gas emissions as well as an issue about local noise disturbance and air pollution (Pellman, R. 2008). Even though residents are often a primary concern to policy makers; they were not modelled in the Set 1 and Set 2 simulations of the research phase as they would not be involved in the ICT decision-making process for a SME.

2.4.2.9 Non-Governmental Organisations (NGOs)

The term non-governmental organisations (NGOs) represent a broad spectrum of organisations that lobby authorities and policy makers on specific issues. Within the context of a society's transition to a low carbon economy there are a number of environmental groups that make their voices heard by policy makers. These notably include Greenpeace and the World Wide Fund for Nature. The process of stakeholder engagement was championed by NGOs during the 1990's as a way to improve the planning process for new civil projects and as a way to achieve a more equitable outcome (Wheeler et al, 2001). While the opinions of NGOs are often of interest to policy makers, they were excluded from the simulations in this thesis because they are unlikely to directly affect the purchasing behaviour of SMEs. It is feasible that the information campaigns conducted by NGOs may affect the preferences of the decision makers within the SMEs, but this could be accounted for within the preference parameter within the Set 1 and Set 2 simulations.

2.5 Policy Options

Here the different policy options available to governments and how they relate to policy objectives and stakeholders are discussed. A range of policy options are examined. While this thesis focussed on carbon taxes in the research phase future work could
examine and compare different policy options, thereby giving policy makers an extra tool for decision making when selecting between options.

2.5.1 Command and Control

Command and control policies are those that mandate specific performance criteria or an activity by a body operating within the legal remit of an authority or government. A prime example would be the “end-of-pipe” regulations applied to the coal fired power stations in the United Kingdom throughout the 1950’s (Griffiths et al, 2011). These have the advantage, when technically possible, to have policy goals achieved through mandate. However, it can mean that firms that do not have the technical skills to meet the new regulations are adversely punished (Le Grand, 2009). While the Set 1 and Set 2 simulations in this PhD project do not directly model command and control policies, they can easily be adapted to do so if required by future research.

2.5.2 Tax Breaks and Incentives

A popular method for encouraging the uptake of low carbon programmes amongst the private sector is the use of tax relief or tax breaks on projects that meet pre-set criteria. In such situations tax-levying authorities remove tax liability on projects, for example projects that are designed to produce electricity from wind turbines. The tax breaks are usually for a fixed time period in order to encourage initial investment, but not give a long term advantage that could be considered as unfair (Carley, 2011). The carbon tax modelled in the simulations in this thesis is analogous to the UK’s climate change levy.

2.5.3 Tradable Permits (Cap and Trade)

In a tradable permit scheme, there are a finite number of “permits” that allow for a fixed amount of emissions by a polluter. These permits are then allocated amongst the applicable firms who are free to consume them in the course of conducting their business or sell on any extra permits to gain an added income. Therefore, there is a strong incentive for firms in the tradable permits scheme to become more efficient and gain an added competitive advantage from the revenue derived from sale of extra permits (Colby, B. G. 2000). The European Union has a scheme known as the Emissions Trading Scheme (EU ETS) which came under criticism during the early 2000s for allocating too many permits amongst participating firms. The result was that the value of the permits fell too low to provide an incentive to trade and there was not the desired reduction in carbon emissions that had been anticipated as a result of the scheme.
(Anthoff and Hahn, 2010). This concept was excluded from the simulations, because at the time writing them the UK did have a permit scheme for SMEs with respect to GHG emissions. However, should this change it is possible to upgrade the simulations to add the scheme.

### 2.5.4 Awareness Campaigns

The Carbon Trust and the Energy Savings Trust in the United Kingdom both run awareness campaigns to encourage the general public to reduce their greenhouse gas emissions. Both the Carbon Trust and the Energy Savings Trust are not-for-profit entities that were founded by the United Kingdom government as mechanisms for encouraging a low carbon economy. (Hall et al, 2010). These awareness campaigns were not directly modelled in the Set 1 or Set 2 simulations. However, it is conceivable that they would affect the opinions and preferences of the decision makers in the SMEs and therefore could indirectly affect the outcomes. This is incorporated in the model where each SME has a decision maker who has a set of preferences.

### 2.5.5 Carbon Taxes

There are a number of policy options revolving around the taxation of fossil fuels in order to encourage a reduction in their consumption. Using the UK as an example, there are a number of carbon taxes varying in size depending upon which fuel is being consumed. For example, fuel duty for consumption in motor vehicles is charged per litre at the point of refuelling and the tax levied on coal is applied at the point of consumption by the utility company. These taxes are then normally passed on to the customers (Feng et al, 2010). This tax on coal was later superseded by the climate change levy. The Climate Change Levy was directly modelled in the Set 1 and Set 2 simulations and varying its size produced different observable emergent behaviour in the marketplace – discussed in greater detail in the methodology, results and conclusion sections of this thesis.

### 2.6 Quantitative Methods in Assessing Policy Efficacy

As discussed above there are many and varied policies which can affect decision making within the ICT industry. The stakes for governments to examine the effectiveness of their policies can be very high (Flitcroft et al, 2011). Whether it is for the purposes of re-election or preventing the failure of the country’s agricultural industry, the ability for
policy makers to predict the outcomes of a proposed policy prior to implementation is of enormous value (Turnhout, E. 2009). This is because it is often the case that by the time there is historical data, it is often too late to make changes that could make a policy a success. This is partly because of the lack of laboratory conditions available to social scientists (Jackman, S. 2000). Once a major government policy is introduced to a market, it has changed the parameters for the participants (Allenby and Rossi, 1999). For many policy researchers, there is a great deal of difficulty in proving the efficacy of policies in free market economies, even in "command and control" economies there was often difficulty in quantitatively demonstrating the outputs of their policies (Bailey and Rupp, 2005) However, in free markets, where consumers are operating without direct instruction from central government on how to consume and the tools of production can respond to market demands, it is often necessary for researchers to wait until after policies are enacted and observe the effects retrospectively (Mohanty and Langley, 2003). In this section, the various methods of examining the correlation between parameters are explored.

### 2.6.1 Econometric Methods

A common method to examine the correlation between parameters in a system, using time series datasets, is to use a statistical methodology called econometrics. This is particularly useful in the analysis of issues on a macroeconomic level (Keeble and Walker, 1994). For example, when analysing the relationship between central bank interest rates and the average house price economists would use historical times series datasets of central bank interest rates, house prices, gross domestic product, average debt burden, average income and all the other parameters that are expected to relevant. Then using ordinary least square regression (or more advanced statistical techniques), calculate the relationship between interest rates and house prices.

Even though they come from different academic disciplines, econometrics from statistics and economics, and agent-based modeling from computer science and sociology, the techniques of econometrics and agent-based modeling can both be applied for very similar research purposes. Occasionally, they have been simultaneously applied by researchers on a specific problem (Takama, T. 2004). They are both useful for policy makers wishing to forecast the likely impacts of their policy interventions. Using the example from earlier in the chapter, once the relationship between central bank interest rates and house prices are calculated then the change in the average house prices, within a given probability, can be determined. The emergent behaviour patterns
of agent-based models can be used by policy makers in a similar way (Zimmermann et al, 2001).

Econometric models can be used to apply the results from econometric analysis for forecasting purposes. Coefficients calculated from the analysis can be applied to the parameters of interest (West, K.D. 1996). This analysis is useful when using extensive amounts of real life data and then supporting trend analysis used in forecasting, it may not always be possible to consider the effects of institutions (Onorante et al, 2010). However, econometric models can be used to generate a probability based forecast with assumptions based upon real life observations and calculated relationships (Covas et al, 2014). It could be of interest to compare and contrast the forecast results of the agent-based models produced in the Set 2 models in the experimental phase of this PhD project with an econometric analysis of historical time series data of UK ICT sales figures. However, as is often the case with econometric analysis, this is likely to be limited by the quality of availability data and the inability to accurately account for “shock” events like that of a sudden implementation of a new tax or change in the market conditions (such as a stock market crash).

2.6.2 Equation Based Models

Before the use of agent-based models, many researchers would build equation based models (which are still often used), where an algebraic solution is found for a system reaching a static equilibrium (Lian and Plott, 1998). A good example would be the work by Sklar and Constanza in 1985 examining the issue of population growth (Sklar and Constanza, 1985). These models can also be solved using linear programming (Bemporad et al, 2002). This type of modeling requires extensive skilled input and cannot easily solve large complicated systems with large datasets. Hence, they are not ideal for when a researcher wishes to observe the aggregated effects of thousands of entities in a market place. They are also limited in their usefulness in finding the emergent behaviour of a social system often desired in policy analysis.

Closely related to this kind of modeling are “system models” where stocks and flows of information, material or energy are represented as sets of differential equations linked through intermediary functions and datasets and time (Philips P.C.B. 1991). However, dependent upon how these models are applied, for example if the results of multiple variations are aggregated, there is effectively an equivalent to a simple ABM. Though the
distinction can become blurred it would be largely related to how much data is stored between time steps; a defining principle of ABMs is that data is stored between time steps in order to discover emergent behaviour (Grimm et al, 2010).

Algebraic models are useful for finding static equilibriums – for example in a Walrasian economy (where the prices of goods and services adjust to equalise supply and demand (Gul and Stacchetti, 1999). However, these are less useful for examining emergent behaviour in dynamic systems where parameters change over time, for example with the research question in this thesis where the impacts of increasing carbon taxes are under inspection. The use of equations based models was not considered for this PhD thesis, however, learning how they are created and applied helped to inform the methodology applied to the creation of the ABMs used in the experimental phase that developed the Set 1 and Set 2 models.

2.6.3 Cost Benefit Analysis

Throughout this chapter there is the comparison of different methodologies available to policy makers for analysing the effectiveness of their polices and judging the policy future outcomes. Cost Benefit Analysis (CBA) is commonly used in business economics to support the decision-making process for management (Li et al, 2009). It can also be used by policy makers comparing polices with known desired outcomes. CBA tends to focus on one-off decisions, for example firms choosing between different capital equipment investments options (Kahraman et al, 2002). In a CBA, the total costs of a decision option are summed sequentially and total benefits of the same option are summed in a similar fashion. This process is repeated for each option being assessed and directly compared to its rivals, typically using their total financial costs (although another impact, such as greenhouse gas emissions could be used). However, CBA can only be used on one target subject at a time and cannot be used to simultaneously calculate outcome of numerous firms operating in a virtual environment. Generally, CBA are not necessarily designed to cope with random events (“fuzzy techniques”), although many analysts using such techniques will indicate the probabilities of outcomes occurring. One example of CBA would be a company accountant issuing an annual report and giving their predictions of the firm’s financial status in the next year based upon known overheads, customer orders and so on. This compares poorly with ABM methodologies which allow for researchers to use agents that store information between time steps and observe emergent behaviour (Joyce et al, 2002).
With respect to this thesis it could be argued that each individual SME agent is conducting a process analogous to a CBA, with its own specific preferences and endowments, for every time step in the simulation. CBA is not designed for aggregated analysis (Lakic et al, 2015), which with respect to this PhD project is of vital importance. The objective of policy makers is to influence the market place in order to achieve societal aims, in this case the reduction of greenhouse gas emissions and improved energy efficiency.

2.6.4 Input/Output Models

Input-Output models are a social accounting matrix often used by researchers to examine macroeconomic changes in national economies (Okuyama and Santos, 2014). However, they are not as applicable where consumer choice is an important factor on a granular microeconomic level (Lave et al, 1995). Such as in this thesis’s research question where the effects of a carbon tax in the ICT market is examined. Therefore, there was not the need to examine them as research method very closely as they were dismissed as an option very quickly.

2.6.5 Agent Based Models

There were several modelling options available for the examination of carbon tax policy effects on the ICT market, some of which are discussed earlier in this chapter. What follows is a brief discussion of what agent based modeling is and why it was selected for the experimental element of this PhD thesis that developed the Set 1 and Set 2 models.

The principles behind agent based modeling (ABM) are relatively simple. However, ABMs are highly scalable, iterative, interactive and adaptable (Fei and Chen, 2007) – therefore offer a number of ways that they can applied to a myriad of social and economic research problems (Huang et al, 2014). In an ABM, a system is created where software actors are modelled in such a way that they can interact with each other and their modelled environment. These interactions generate a history and can hence influence future interactions depending upon the assumptions and preferences in the system and the decisions made by the software agents (Jennings, N.R. 2000). ABMs are often useful when there is a lack of “hard” real life data to trend from and can be used to develop a “bottom up” analysis of situations and potential responses. For example, the behaviour of users of a waste transfer site could be modelled using known preferences of likely users and the emergent behaviour at the waste transfer site could be modelled using an
ABM (the aggregated iterative of all the user agents observed over the desired number of time steps) (Bresciani et al, 2004). If the agents are realistically designed then there is academic interest in observing the behaviour of the model. ABM methodology is also useful in sensitivity analysis where the level of complexity can be controlled. A classic example is the study conducted by Grimm and Railsback into the requirement of fox poison in the management of rabies in continental Europe. They were able to successfully predict the level of poison deployment that would eliminate enough foxes to control the spread of rabies (Grimm and Railsback, 2010). Their results were used by forest managers and they reduced the number of flights dropping poison saving significant sums of money without affecting protection against rabies.

The mathematician and social scientist Joshua M. Epstein is a famous early proponent of agent based models and has some useful explanations as to why ABMs are of academic value (Epstein, J.M. 2007). In particular, their iterative qualities allowing the researcher to both observe emergent behaviour and calculate forecasts based on repeated iterations and trend analysis, as conducted in this thesis. Epstein developed historically accurate models of the ancient Anastasi tribe in North America, to determine possible reasons for their disappearance. Very similar principles were applied to the Set 2 models in this thesis, where the SME agents were allowed to arrive at a solution using their decision profiles and endowments. Epstein was able to combine geography, agriculture, demographics, historical events as well as other valid parameters to produce a number of realistic emergent behaviour scenarios.

The usefulness of ABMs to test hypotheses was also championed by Epstein, Axelrod Gilbert, and others. They concluded that ABMs could indeed be used to test hypotheses even when there was only indirect evidence (Chen et al, 1999). For example; agent based models to support predictions about the use of land under different low and high frequency environmental conditions – such as building structures, housing density, pricing and so on (Magliocca et al, 2011). Similar ABM research techniques have been used to illuminate the relative importance of, and interactions among, various demographic and environmental factors in the processes of sociocultural stability variation and change. Hence the careful selection of the parameters in the models created for this thesis.
2.6.5.1 The Early Days; Von Neumann

What follows is a brief description of the origins of agent based modeling. Social scientists cannot perform controlled laboratory experiments in the same way as many other scientists can and this causes difficulties in generating tests for hypotheses other than retrospective examination of data (for example econometric analysis). Arguably the first description of an agent based model where individuals were modelled as entities that could be aggregated and had individual objectives was by von Neumann in his 1966 work on self-replicating “automata” (Sarkar, P. 1999). This fundamental principle inspired the development of “artificial societies” where agents are able to be “born, feed, reproduce and die” – subtly different from the software agents later in this thesis, these early agents did not trade in a financial space. However, von Neumann’s work inspired countless research projects, papers and books and led, ultimately, to the field of automated computational economics (ACE) discussed later in this section. The fundamental principles of artificial societies, ABMs and ACE research remain the same; software agents interact with each other and/or their environment and carry forward into the next time step the results of their activity in the previous one (Epstein, J.M. 2007).

2.6.5.2 Swarms

A significant development towards the software agents used in this thesis were the creation of “Swarms”. These are simple computer simulations where researchers use a virtual geographical space populated with simple software agents representing birds, bats, fish, etc. and their interactions are modelled using simple rules. These are significant developments because they were able to demonstrate emergent behaviour when combined with a time history. Swarm society models where the individual agents respond to the movements of each other and “flock”. Examples include Raynolds’ “boid” software bats that fly around each other in a geographical space mimicking the behaviour of real bats (Miki and Nakamura, 2006). These swarm type simulations contrast significantly from simulations such as Sugarscape (a famous early social simulation from the 1970s by Axtell and Epstein where the agents interact, feed, breed, trade and die) as they do not trade – see section 2.6.5.3 for further discussion. However, the ability of Swarms and social simulations like Sugarscape to mimic real life behaviours was a significant step in computational modeling and helped progress researchers towards the use modern agent based models. Indeed this principle is
fundamental to the assertion that forecasts can be made using the Set 2 models discussed later in this thesis.

Software platforms were developed to quicken and standardise research methodologies, rather than coding the model from first principles with every research project, researchers were given the opportunity to use pre-set commands to populate a virtual space with software agents that could be programmed with simple preferences and constrained with defined parameters. NetLogo is an example of such a platform, it is highly optimised for geographical models and provides sociologists with a useful research tool for observing theoretical emergent behaviour in social groups (human or otherwise).

2.6.5.3 Sugarscape’s Trade Algorithm

Epstein and Axtell’s seminal artificial society known as Sugarscape drew heavily on Slutsky equation in their “Trade Algorithm” and in turn it inspired the trade protocols in the agent-based models in this thesis. It was originally designed for trades of “sugar” and “spice” between agents in Sugarscape to increase their utility (Oremland and Reinhard, 2014). In the models developed for this research this principle was used to inspire the protocol for the SME agents investing in ICT options. Then in the second generation of models, where ICT providers are agents as well, it was used to inform the trade within this updated model. What follows is a description of how the Sugarscape Trade Algorithm was adapted for use in the models and how the principles of marginal rate of substitution and utility maximisation, or in these cases profit maximisation, were applied.

In Sugarscape, as with most agent-based computer simulations, “trade” is used to denote a transfer of stocks from one agent to another (one of the agents can be passive as in the Set 2 Model A where the ICT providers are passive). This trade can be conducted without the agents having a mechanism for calculating welfare gains. However, because the simulations in this thesis are designed to provide an economic analysis the trades have to improve the welfare of both agents in the trade. Also, in Sugarscape, “sugar” and “spice” can be bartered. The models in this thesis operate solely on the exchange of money for goods or services. Profits are a proxy for utility, increased profits result in increased utility, the SME agents in the Set 2 models profit maximise.
Since discrete quantities are being traded, and therefore repeated exchange may never lead to an identical agent marginal rate of substitution (MRS), special care is needed to avoid infinite loops in which a pair of agent alternates between buyers and sellers (Li and Zhang, 2008).

Putting it all together, Epstein and Axtell came up with a vector known as the Agent Trade Rule $T$

- Agent and neighbour compute their MRS if these are equal then end the interaction, else continue to exchange:
  - The direction of the exchange is as follows: spice flows from the agent with the higher MRS to the agent with the lower MRS while sugar goes in the opposite direction
  - The geometric mean of the two MRSs is calculated – this will serve as the price, $P$
  - The quantities to be exchanged are as follows: if $p>1$ then $p$ units of spice for 1 unit of sugar, if $p<1$ then $1/p$ units of sugar for one unit of spice
  - If this trade will (a) make both agents better off (increases the welfare of both agents) and (b) causes the agents MRSs to cross over one another then the trade is made and return to start, else end. (Epstein and Axtell, 1996)

Note that the bargaining rule constitutes step 3 of the algorithm used in the thesis.

[Given $\text{MRS}_A > (\leq) \text{MRS}_B$, agents stop trading if one additional trade will make $\text{MRS}_A < (\geq) \text{MRS}_B$.] For a graphical representation of $T$ consider the so-called Edgeworth box (Gabaix, X. 2014). For example, in figure 2.2; where Agents A and B have different endowments of goods X and Y and they also have different, overlapping, marginal rates of substitution allowing for a “negotiation space”. Figure 2.2 is a typical representation of an Edgeworth Box as used by Epstein and Axtell, it shows the opportunities for trade between two agents (A and B) encountering each other with different endowments of two goods (X and Y).
Therefore, a trade protocol is developed where the following questions need to be answered:

- When will the agents trade?
- How much will they trade?
- What price will they trade at?

In a neoclassical approach to the theory of general equilibrium – a centralised market run by an “auctioneer” can arrive at an equilibrium price vector for the entire economy, i.e. a set of prices at which the markets clear, supply matches the demand.

However, in an agent-based model, as with real life in a free market economy, there are no centralised auctioneers controlling the information seen by all the market players. Epstein and Axtell, working from Kreps’ 1990 paper “Why (not) believe in Walrasian Equilibrium?”, based the trade algorithm on imaginary consumers wondering around a large square with all of their possessions (endowments) with them (Epstein and Axtell, 1996) having chance meetings with other consumers. The Walrasian model describes a situation where pricing plays the crucial role in coordinating the distribution of goods. To introduce the Walrasian model it is best first look at a pure exchange economy. An exchange economy is an economy without production. There are a limited number of economic agents and a finite number of commodities. Each economic agent has an endowment of commodities. In this theoretical model the world is set to end and all the
economic agents will consume their commodities, but before this happens there is an opportunity to trade their commodities at set prices. Walras wanted to know if there existed prices such that, when all the economic agents traded their desired amounts of commodities at these prices, demand will just equal supply, whether it will be an efficient allocation will depend on preferences and endowments (Levin, J 2006).

When two consumers meet in Epstein and Axtell’s Sugarscape model, they examine each other’s endowments and, if a mutually beneficial (hence the importance of marginal rates of substitution), trade is possible where both parties improve their utility (in this case an increase in profits), they do so and carry on wandering randomly in search of other advantageous trades from chance meetings (as discussed in the previous paragraph in more mathematical terms). This principle is the foundation of the assumptions of how the trade between the SME and ICT Provider agents occurs in the Set 2 models discussed in chapters 4, 5 and 6. This was possible as hardware and “cloud” services are performing the same functionality for the SME agent, even if they are not perfectly interchangeable goods (Jeffries et al, 2001). The action of the probabilities of events occurring was applied to further the realism of the simulation.

This precept of how the trades occur was the original inspiration for how SME agents select their basket of goods (“cloud” versus hardware) especially in the Set 1 NetLogo generation of models discussed in chapters 4, 5 and 6. It was heavily modified for the research in this thesis; the SME agents purchased goods (the ICT hardware) or services (“cloud”) with money rather than simply exchanging goods from endowments. SME agents did not trade with one another, they purchased goods or services from ICT provider agents. Originally these were passive [responding to purchase requests from SME agents] in the Set 2 model A versions. However, in the later, Set 2 model B autonomous ICT Provider agents were added with profit maximising objectives.

2.7 Conclusion to Chapter 2

The United Kingdom has a long history of environmental policy– for example the clean air act of the 1950s where controls were placed upon coal fired power stations and this then reduced the levels of smog in the country’s cities (Bailey and Rupp, 2005). This was an example of a “command and control” policy where the government dictated how industry was to respond. However, in the modern liberalised marketplace the ICT industry operates in the UK there is a greater preference for government to use
incentives and taxes to shape outcomes. Carbon taxes provide an income for government while incentives systems – for example a subsidy for a new technology - cost the government. However, subsidies often have the benefit of “kick starting” an emerging technology. Hence the use of “feed in” tariffs to support the adoption of solar energy technologies while they remained economically disadvantaged compared to low cost fossil fuels (Lipp, J. 2007)

After covering a broad range of factors and policies earlier in this chapter, it is important to try and trace a mental picture of how they aggregate to affect the ICT industry and drive reductions in GHG emissions. With so many factors at play it is difficult to intuitively predict which are the most relevant. However, that is the beauty of research, there is always the opportunity to improve our understanding of the world we live in. ICT firms and their customers operate in a wide world. There are opposing economic forces, short-term profits versus long-term policy objectives. This is often a difficult place for policy designers in western style democracies to operate in, their political masters are often concerned about their electoral cycles and wish to be re-elected every four to five years, and can push for visible results to be demonstrated within that time-frame. It can often take economies longer than five years to adapt to technological progress or changes to the market from new policies.

Environmental policy is generally applied to the ICT sector in either a command and control fashion (where government dictate targets to market participants, for example the eco-design directives discussed earlier in this chapter) or where policy is designed to influence the market through incentives and disincentives (for example eco-labelling). Environmental policy within the EU, combined with economic factors such as energy price rises have reduced the average energy consumption associated with an individual computer over the past decade. Much of this reduction is as a response to a change in the transformer technology and improved CPU chipsets that do not draw as much power as previous generations. However, due to the increased total amount of computing power demanded by society, the absolute amount of electricity consumed and hence the greenhouse gases emitted, has continued to increase. The policies discussed in this chapter are designed to reverse this trend and result in reduced absolute GHG emissions without reducing economic activity.

Policies designed to increase the energy efficiency of computing hardware and software must be combined with polices designed to encourage consumers to reign in their
energy consumption. Otherwise there is a real possibility to experience the “rebound effect” – the effect seen when increased energy efficiency leads to the increased absolute consumption of fuel due to increased economic activity from lower input prices. Also, with the increased usage of “cloud” systems due to reduced costs per user there could be increased energy consumed across society as the use of Internet networks and datacentres increases to meet demand for “cloud” services as well as the associated embedded energy from the construction of the associated infrastructure. Therefore, behavioural change is important to reduce the energy consumption of ICT.

There is also the question as to whether the embedded energy consumed during the manufacture of devices has a greater environmental impact than the in-use consumption. In the case of servers there is a significant amount of evidence to suggest that the energy consumed in the “in use” phase is far more significant than the energy consumed in their manufacture and that switching to low energy servers recoup their embedded energy within a year.

At the time of writing, none of the policies in the European Union require a full life cycle analysis (LCA) of the devices sold by manufacturer. There are feasibility studies in France with the Grenelle project to phase in compulsory eco-labels stating the associated CO₂ emissions for products sold. If the merits of such LCA analysis were accepted, there is the possibility that ICT firms would resist such policies due to the increased development costs. It is probable that they would argue that such a policy is anticompetitive and limit consumer choice due to ICT firms reducing their product and service offerings due to the higher cost of reaching the market.

The main drivers for change in the energy efficiency performance of ICT products and services interrelate with each other and their relative influences fluctuate. The cost of energy is probably the most powerful driver excluding direct regulatory intervention. These drivers are pushing the industry to make products and services more energy efficient and it could imply that there is continuous room for improvement until energy efficiency is 100%. However, this is not the case; there are strict physical limits to what can be achieved by technology. The universe is bound by the thermodynamic laws and they cannot be broken, hence there is a limit to how efficient physical systems can be at transforming one form of energy into another (Charache et al., 1999). In figure 2:3, there is a schematic representation of drivers discussed earlier in the chapter encouraging improved energy efficiency performance and the upcoming physical limits of what is
achievable with current commercially available technology. Therefore, policy goals have to consider the physical limits of the technology and ICT users may have to modify their behaviour if goals for reduced GHG emissions are strict enough.

*Figure 2:3: Schematic diagram representing the drivers for change encouraging improved energy efficiency performance over time.*

Though there were a number of econometric research methods available in order to examine how policies affect markets the option of using agent based models for carbon taxes influencing SME’s selecting between ICT upgrade options appealed for a number of reasons. Primarily it was the adaptability of the technique, furthered by the possibility of adding parameters and complexity as required which made the research progressive and allowed for sensitivity analysis. The trade methodology developed by Epstein and Axtell inspired the methodology discussed in Chapter 4.
Chapter 2 References:


BOQUET, Y. 2010. FROM PLU TO ECO-PLU: STRATEGIES FOR A SUSTAINABLE CITY IN DIJON, FRANCE. Proceedings of the First International Conference on Sustainable Urbanization (Icsu 2010), 1013-1021.


DIRECTIVE 2010/30/EU of the European Parliament and of the Council of 19 May 2010 on the indication by labelling and standard product information of the consumption of energy and other resources by energy-related products (Text with EEA relevance)

DIRECTIVE 2009/81/EC of the European Parliament and of the Council of 13 July 2009 on the coordination of procedures for the award of certain works contracts, supply contracts and service contracts by contracting authorities or entities in the fields of defence and security, and amending Directives 2004/17/EC and 2004/18/EC (Text with EEA relevance)


Chapter 3: Determining the Research Question

In this chapter of the thesis the journey towards the final research question is discussed. The process drew heavily from the academic literature review discussed in the previous chapter. It became apparent that there were two clear strands for the research.

Input from industry experts helped to shape the research. A number of industry experts were interviewed in a number of sessions. In particular there were three experts, preferring to remain anonymous, who were repeatedly interviewed over a period of four months. They included an IT manager at a local borough council, a systems architect who has a large number of SME clients and a “cloud” specialist who works for a multinational insurance company. In addition, a significant number of industry experts from Hewlett-Packard were also canvased for their feedback.

A significant section of the ICT market place is the small and medium sized enterprise (SMEs) sector (Maryska, M. 2013) and their exposure to carbon taxes is an interesting development to examine. SMEs often have greater sensitivity to changes in their overheads than multinational organisations (MNOs) as they are more susceptible to business failure if their cash flow becomes negative (Camacho-Minano et al, 2015). SMEs are potentially less able to absorb costs or increase lines of credit than governments or large multinational firms and hence a carbon tax applied to electricity consumption changes the cost structure of using ICT services and hardware. When a consumer has purchased ICT hardware they must pay for electricity to run the device. However, if they are using a managed service, such as a “cloud” service the provider of the service pays the electricity bill (Zhang et al, 2011). If a carbon tax is applied to the market, the ICT client will see a linear increase in the cost of using their hardware. However, because service providers are able to achieve economies of scale and use virtualisation and higher levels of hardware optimisation on their ICT infrastructure, they are often able to produce lower rates of energy consumption per user than those seen in client hardware installations (Beloglazov and Buyya, 2012). This is one of the relationships examined by the computer simulations in the research phase of this PhD project and helped influence the emergent behaviour of the models.
The focus of the Set 1 and Set 2 computer simulations, discussed further in later chapters, are the small and medium enterprises based in the UK who are procuring either an upgrade of their fixed ICT hardware installations (servers, PCs, etc.) or hosted managed remote infrastructures (commonly known as “cloud” solutions). With the introduction of the climate change levy (discussed in chapter 2), there is a possibility that UK based SMEs change their procurement behaviour. This raises the interesting question addressed in this thesis of modeling the market to predict the likely impacts of the CCL at differing levels of burden.

Since the publication of the Stern report in 2006, as discussed in Chapter 2, (Stern et al, 2006) the UK government has set targets to domestic industry to reduce their GHG emissions. There is also an emphasis on how the UK government’s Carbon Reduction Commitment Energy Efficiency (CREE) policy increases the price of electricity and hence affect the cost overheads faced by client firms and households (Rosenow et al, 2013). The relationship between upfront costs, total ownership costs and other considerations including data protection and what is “best practice” inform the Set 2 model simulation’s key parameters. The security and reliability of a firm’s network is always paramount in the mind of the ICT manager.

The following research topics were formulated following the literature review in chapter 2:

• What is the feasibility of using agent based models for analysing environmental policies?
• What are the impacts of carbon taxes on ICT procurement?

The research questions fill a gap in knowledge as well as a niche that is both academically and commercially interesting. The process of reading broadly also helped to observe how there were similarities across most EU environmental policies. Governments have a desire to have environmental benefits without incurring excessive economic costs, as shown in figure 2.1.
3.1 Aims and Objectives of the Research

The primary aim of the research is to examine whether it is feasible to examine the potential influence of environmental policy – in this case the use of a carbon tax on electricity consumption - on the purchasing behaviour of key decision makers in the ICT marketplace using agent based modelling techniques. Put in other words, the feasibility of using agent based models (ABMs) to examine the influence of a carbon tax on the procurement of ICT hardware and services.

Another important goal of the research was to see if it was possible to examine emergent behaviour and construct forecasts of the ICT market responding to differing levels of carbon tax. This could theoretically allow policy makers to determine the optimum level of taxation to produce the desired reduction in electricity usage and corresponding GHG emissions. This is of practical and academic interest; policy makers would have a tool to forecast the impacts of carbon tax levels. It also allows ICT firms to model the effects that policies might have on their market and model the results of their responses – for example price changes or changes in products and services offered – that would affect the preferences of ICT managers. This is often key in the ICT sector where functionality is a key differentiator and price is often a secondary (albeit a major) concern.

The methodology in chapter 4 includes a discussion of agent based models, the main research technique of this PhD project. There is also a brief comparison of alternative techniques and methods that are often applied by academics and policy makers to analyse and/or predict the effects of policies.
Chapter 3 References:


4.1 Introduction

In this chapter the theories, methodology, techniques and parameters used to formulate the computer simulated models and generate the results of the experimental phase of the research are discussed. The process of development of these models was not pre-set at the start of the PhD and several approaches were used as knowledge developed. This chapter outlines the most salient elements of the approaches and discusses the workings of the final simulation models. Set 1 models were written in NetLogo and the final simulation models, A and B, of Set 2 were written in Java using the Eclipse development environment. The primary purpose of the preliminary Set 1 models was to test the feasibility of modeling the effects of environmental policy on ICT procurement and this informed the process for the Set 2 simulations which were designed to produce experimental results. This section also details how the models were put together, to allow for replication, verification of method and future research.

4.1.1 Overview of Models Set 1 and Set 2

What follows is a brief description of how the models in the simulation in this thesis are designed to operate and simulate the response of UK SMEs purchasing behaviour with respect to ICT to changes in carbon taxes.

Set 1

- The Set 1 models are written in NetLogo and operate in a manner often used in agent based modeling, where the NetLogo platform was used to create “turtles” (agents) which are then given properties to operate in a 2-dimensional space.
- The SME agents were coded for preferences (between “cloud” services and hardware) and endowments (monthly budget per user). They were then allowed to interact at random with the ICT Provider agents.
- At every time step (from t=0 onwards) the SME agents select how much they spend on “cloud” services and hardware per user. They can purchase any combination of the two options and they must utilise their entire per user budget.
In this simulation, as in real life, the ICT provider agents are coded to have overheads. They have to make a profit to survive and price their offerings accordingly. If the ICT provider agents fail to make a profit they are removed from the simulation, reflecting the real-life scenario of a company leaving a market place.

Only the SME agents are visible in the Set 1 model results graphs and their position on screen reflects their spending because they are travelling in a "money space".

The further along the SME agent turtle is on the x-axis, the more the SME is spending on "cloud" services and the further along the y-axis, the greater the expenditure on hardware.

The SME agents consider the cost of the carbon tax in the running cost of the ICT option they are looking at and their position in the "money space" depends on their preferences and budget constraint.

**Set 2**

Rather than operating in a money space, the Set 2 models operate in an information space, with each SME agent given preference and endowments. In this model ICT is a factor of production for the SME agents and the amount of ICT hardware and services purchased in one time step affects the revenue of the SME agent in the next time step.

When the simulation starts, each of the 10,000 SME agents is given a random revenue around a mean (which is based on ONS data and hence is left hand skewed), from which the budget constraint for ICT is calculated (again based on ONS data on average SME expenditure on ICT). A set of random preferences (based upon information gathered from industry experts) are coded to the SME agents with respect to their preference of ICT hardware versus "cloud" services. To reflect real life SMEs in the UK, 3% of the modelled SMEs are set to have a revenue of over GBP1.5 million.

In the Set 2 Model A the ICT providers are passive. In the Set 2 Model B the ICT provider agents are active, i.e. the move around in the information space randomly interacting with SME agents for trade.

At the start of the simulation the SME agents take their ICT budgets (calculated from their revenues) and go to market to select how much they spend on ICT hardware and "cloud" services. The prices of the ICT hardware and "cloud" services in the Set 2 model were based on a per user hour basis, real life market prices and an assumption that hardware is on a three-year life cycle. It was also
assumed that the users operated a 37-hour week and the time steps in the simulation were quarter of a year. The price of the ICT hardware is affected by carbon tax; the carbon tax is added to the cost of the electricity, (based on 300W for 1 desktop per user and a price range of 8p – 20p per kWh) which is then added to the cost of ICT hardware. “Cloud” services include carbon taxes in their hourly rates and due to high levels of hardware optimisation and economies of scale seen in datacentres it was assumed that carbon taxes would not affect the per user hour price of “cloud” services.

- The preferences of the SME agent are treated as Cobb-Douglas preferences and dictate the marginal rate of substitution between ICT hardware and “cloud” services for a given budget constraint. However, at each step, a minority of the SME agents are selected at random to move towards the average spending pattern of the total SME cohort. This reflects the real life of practice of ICT managers at SMEs sharing best practice. The SME agent is then ready for the next time step.

- At the start of the next time step the expenditure of SME agents on “cloud” services and ICT hardware is taken as investment and applied into a Cobb-Douglas production function – whose coefficients were taken from Hempell’s time series econometric analysis of ICT usage in German SMEs (Hempell, T 2002). The output of this equation is used to calculate the revenue in the current time step and in turn the new ICT budget. The assumption was that the aggregated usage of ICT in Germany and the United Kingdom was similar enough to use data from German SMEs into a simulation of SMEs in the United Kingdom (OECD, 2003).

- The process described in the previous two paragraphs is ready to be repeated until the prescribed end point is reached. At the end time step the simulation prepares a data file and three graphs. The graphs display the production v “Cloud” budget, lnProduction v ICT Hardware and Hardware v Cloud Budgets.

- The Set 2 Model B operates in a similar way to the Set 2 Model A simulation with the addition of 10 ICT Providers agents (any number of ICT providers can be selected). The ICT Providers have to make a profit to remain in the simulation. They have overheads and investment costs which need to be accounted for and this feeds into the pricing of their offerings. All of the ICT provider agents offer both “cloud” and hardware offerings. Again, the pricing structure is on a per user basis. Investment costs were taken from published articles about companies entering the UK market. The ICT provider agents were coded for a
number of inbuilt factors including price, service level agreement and reputation. In the simulation the ICT providers and SME agents interacted at random. Only if the ICT provider met all of the requirements of the SME agent did a trade take place.

- At the end of the Set 2 Model B simulations the same data is published as for Model A.

*Figure 4.1: Schematic diagram of the algorithm driving the SME agents in the Set 2 model.*

The process of a time step (1 to 5):

1. **Opening Parameters**
2. **Results determine Production at SME<sub>n</sub> and Total ICT Budget for SME<sub>n</sub>**
3. **Preferences and MRS determine:**
4. **ICT Cloud Budget**
5. **ICT Hardware Budget**

**Adapted Hempel Equation**

\[ \ln Y_{SMEnt} = \ln(\text{ICT}_{Cloudnt}\cdot 1 + \text{ICT}_{Hardwarent}\cdot 1) + 0.686 \ln l_{SMEnt} + 0.189 \ln K_{SMEnt} + C \]

Coefficients 0.686 and 0.189 were taken from Hempel’s analysis.

The detail of how the models were devised and coded is discussed in Chapter 4, the results are discussed in Chapter 5 and the pseudocode is included in the Appendix.

### 4.2 Formulating the approach

Having a clear research question (as discussed in chapter 3 of this thesis) served as a guide and filter for navigating the different research options available. The research question, to examine the specific effects of varying carbon tax would have on the purchasing decisions an ICT manager at an UK SME, was the topic that shaped the investigative methodology. It made identifying suitable parameters and boundaries for
the model easier and helped to produce coherent computer simulations capable of useful policy research. It also made it easier to ask pertinent questions to industry experts who were instrumental in determining the important parameters and hierarchy for the models' operation.

Once an agent-based modeling approach was decided upon, it became clear to start with ICT procurement decision makers as the basis of the first agents. For most EU countries SMEs represent the biggest employment sector at 70% and generate approximately EUR 3.9 Trillion into the EU 28 economy (https://ec.europa.eu/growth/smes/business-friendly-environment/performance-review-2016_en#annual-repo) last accessed 2nd March 2017). Therefore, their aggregated procurement decisions have a significant impact on the rest of the ICT market. On an individual basis, the SMEs are price takers for ICT as they do not have the market power to influence the prices demanded by large ICT multinationals for their goods and services. However, due to the competitive nature of SME ICT procurement where numerous ICT multinationals are competing for market share; prices, services and offerings are often in a state of flux as supplier firms vie to gain a competitive edge. By keeping in mind this scenario and the research question; applying a "bottom up" approach it was possible to use the list of desirable parameters shown later in this section (4.8.2) and generate aggregated emergent behaviour (as described in previous chapters (Xie et al, 2007)).

The first stage of the research process was to visualise the perspective of an ICT manager in a typical SME. An example of the approach was to think: "what would be my priorities if I were an ICT manager in a SME?" This process was consolidated by extensively interviewing ICT professionals, examining academic literature, national statistics and commercial reports (for example Business Week, Gartner and company announcements), thereby developing the list of parameters discussed later in this chapter.

While the Overview, Design concepts and Details (ODD) Protocol (often used to standardise the procedure of developing an agent based model and make it easier for researchers to compare notes between research groups) (Grimm et al, 2006) was not directly used, it did closely inform the methodology of the research. Hence the design of the simulation was such that parameters could easily be added and removed to test the sensitivity of the system to changes. Figure 4.2, pictorially represents the process described by Grimm and Railsbeck in 2005 for generating ABMs and progressively
refining them to produce results that “solve” queries (Grimm and Railsbeck, 2011). The word solve is in quotation marks as the ability for an ABM to produce a useful answer to a question is entirely dependent on the realism in the design of the agents, the choice of parameters and boundaries and the quality of the data applied.

**Figure 4.2: An adaption of the agent based modeling cycle proposed by Grimm and Railsbeck in 2005** (Grimm and Railsbeck, 2011). The diagram should be read from “Formulate the Question” as the starting point.

The process described in Figure 4.2 is an iterative one and was repeated many times during the research phase. Each iteration produced observations that informed the adjustments to the parameters or implementation of the algorithm. These observations often followed an emergent pattern that changed depending on the number of time steps the ABM ran for. These observations are more closely discussed in the results chapter in the thesis.

### 4.3 Application of Microeconomic Theory

A significant aspect of this PhD project was the research phase where, the application of microeconomic theory of consumer behaviour (in this case the SME client firms with respect to utility maximisation) and the theoretical behaviour of the firm (the firms
were assumed to be both profit maximising and cost minimising) was critical to the development of useful SME agents in the models. This allowed for the use of several accepted microeconomic concepts such as Cobb-Douglas preferences and factors of production (sections 4.7.1 and 4.8.1 respectively).

### 4.3.1 Consumer Behaviour and the Behaviour of the Firm

In all the models in the research phase the ICT managers/decision makers were modelled as SME agents selecting whether they should upgrade their hardware, purchase "cloud" services or a combination of the two. In the Set 1 models these agents were treated as consumer agents where consumption of ICT leads to them achieving increases in their utility. A utility maximising Client agent was created for the model. In the Set 2 models it assumed that there would also be diminishing marginal returns as investment increased (Fairfield et al, 2003) where ICT is used as a factor of production (an area where this PhD project provides academic novelty in the use of agent based models). The early Set 1 models (written in NetLogo) used the feature of the software that allowed for numerous simultaneous interactions to be calculated. This lead to an iterative progression through time that could be plotted visually in a "money space". The way the money space works is also discussed later in this chapter (section 4.6.4).

At the start of the experimental phase of this PhD project NetLogo was an ideal platform to prove the concept of policy research with respect to the ICT market using agent based models. NetLogo is purpose built for the creation of agent based models for social science research and is optimised with pre-set commands and templates which can be adapted for use by the developer. The preferences between the "cloud" and/or hardware purchases were represented in the Set 1 model by using the parameters called "trust in cloud" and "trust in hardware", (explained in greater detail in 4.6.2 and 4.6.3). Preferences are an important principle in consumer behaviour and along with price, shape the composition of the basket of goods purchased by the consumer for a given budget constraint (Rusmevichientong et al, 2006). It was also assumed that the "cloud" and hardware were "normal goods", as budget constraints increased there was a corresponding increase in the absolute value purchased by the SME agent (Serel and Dogan 2012). However, in real life this is not necessarily the case as ICT equipment and software often have optimum consumption values for maximising per user output (productivity) – i.e. there are often diminishing returns on investment (Aksentijevic et al, 2015).
4.3.2 Profit Maximising Firms and ICT as a Form of Capital

A critical component of the Set 2 models (written in Java) was the assumption that ICT hardware and software could be treated as a form of capital for the firm to be productive. This is an area where this PhD project provided significant amount of academic novelty (at the time of writing there was not any academic material published on the topic) and is explored in further detail later in this chapter in section 4.7.1. It is probable that treating the SME firms solely as consumer agents would leave out the factor that they use ICT as a means of production and they are not simply consuming ICT to provide utility (Hempell, 2006). Since the firms are using the ICT as a tool for their production, this in turn provides them with income. Extending this thought process, we can assume that a firm that performs poorly in their choice of ICT basket could risk going out of business. If their competitors have better-optimised choices of ICT solutions they would gain a competitive edge. The business viability of SMEs (ICT consumer firms) therefore could be affected if their ICT budgets were too small to provide sufficient productivity. It is assumed that they would suffer from diminishing marginal rates of return on investment and if their ICT budgets were too large there would be a loss of competitiveness due to inefficiently allocated funds.

4.3.3 The Microeconomics of Information Technology

In this section, the significance of ICT is more closely examined on a microeconomic level, this is done to better explain the approach to the research method in the models produced. The famous Economist Hal Varian has written extensively on the topic of information & communication technology (ICT) and the microeconomics of the firm. Fundamentally Varian concluded that there needed to be a shift in the neoclassical model with respect to information technology (Varian, H 2014). The way in which ICT costs and benefits occur to firms is fundamentally different to most forms of capital infrastructure. For example, the implementation of a new database software suite to a firm could be in the millions of US dollars, however the marginal cost to the firm of adding a new user to the database (depending on the license agreement) could be virtually zero, taking a couple of seconds for the ICT administrator to add their details to the user list. Also, it can be exceedingly hard for firms to assess the value of their ICT systems to the firm, each contact, copies of communications, CAD designs, etc., are all subjectively valued and it is difficult to accurately assess the true value of ICT system to the firm (Columbo et al, 2013). Even when it comes to assessing productivity of the
users it is difficult to value the usefulness of ICT systems. There are many occasions where ICT is a work multiplier, for example in the creation of mailshots for marketing campaigns, or the creation of blueprints which would be very time consuming to edit via pen and paper can be instantly revised using a CAD system (Columbo et al., 2013). Therefore, firms that are successful early adopters of effective ICT systems can achieve a comparative advantage against their rivals, increasing their productivity and reducing their costs (Ollo-Lopez and Aramendia-Muneta, 2011). This allows them to increase their margins and/or win extra market share with more competitive prices. Additionally, the phenomenon of “lock-in” (Heinrich, T, 2014), where ICT users are tied to a technology solution due to the high sunk costs and the excessive costs to move to a different solution (for example the use of an antiquated database that would prove too costly in man hours to move to a newer, faster database solution), change the procurement behaviour of firms.

Another factor that makes economic analysis of the information technology market difficult is the co-dependency of software and hardware (Di Gaetano, L, 2015). In this research phase the hardware solutions incorporated the software needed to use them (and hence treated as a single entity) with the “cloud” services also incorporating the software required to deliver the service.

User competence in Hempell’s research (Hempell, T 2002) affects economic analysis of ICT usage, but for the purposes of simplicity in this research it is assumed that the general user competencies average out to be equal for all the SME agents. It was assumed that the ICT Managers would be able to train the staff within their firm, therefore the overall average competence across the all the SMEs would be equal. In the work by Hempel (discussed in greater detail in section 4.7.1) coefficients of parameters were calculated by econometric analysis of German SMEs. It was assumed that UK SMEs were similar enough in their usage of ICT to German SMEs (OECD, 2003) to apply these coefficients to the Set 2 models later in the research phase. This was a fundamental assumption in the creation of the Set 2 models.

For the development of early Set 1 models it was assumed that “cloud’ solutions would be an offsite datacentre managed by an ICT provider on behalf of the client SME. Users at the SME were assumed to be using “thin client” devices (low powered PCs that allow the majority of data processing, storage and archiving to be done at the datacentre) and hardware solutions (i.e. the hardware package of a server with operating system and
personal computers for each user) sold as complete suites. Therefore, the ICT managers are selecting completed packages, or hybrid bundles with some investment conduct into both solutions. It is assumed that the "cloud" solution offered would be suitably sized for the client SME and again it is assumed that the ICT managers would specify an appropriately powerful server for their users. In real life there are a number of operating systems, databases, hardware and virtualisation options that can dramatically affect the investment cost. In the simulation, rather than selecting from a wide spectrum of combinations of hardware and software options this was simplified to hardware and "cloud" options. The outcome of the simulation showed the SME budget allocation between the two options.

Varian identified and examined the issue of complementarity in the ICT industry and formulated a Nash equilibrium for a pricing model that considers the situation of hardware and software ICT providers dependent upon one another to access the ICT market place. This could have been used as an alternative approach to solving the research question of this thesis. The Nash equilibrium was not, however, needed in the research phase of the PhD project as solutions were found from the emergent behaviour of the Set 1 and Set 2 agent based model simulations. This highlights the benefits of using ABMs in this type of scenario as the emergent results can be used to solve multivariate equations. This provides evidence to answer the research questions.

**4.3.4 Slutsky Equation**

The Slutsky equation is valuable in microeconomics as it helps model the purchasing behaviour of consumers responding to price changes of goods or levels of income – it represents a function for the substitution effect complimented with a function for the income effect. As the income of the consumer varies the basket of goods they are likely to purchase changes correspondingly. For example, for normal goods such as computer hardware, the higher the price charged, the less that consumers or SMEs will purchase and the substitution effect comes into play as the consumers/SMEs start to buy alternatives. The differential rate at which the consumer/SME alters their purchase of goods varies according to their preferences (it is assumed that ICT services and hardware are normal goods). An adapted version of the Cobb-Douglas production function was then used to calculate revenue; hence a ICT budget could be calculated, related to ICT as a form of capital and is explained in more detail later in section 4.7.1.
4.3.4.1 The Slutsky Equation as it is most commonly used:

**Equation 4.1:**

Below equation 4.1 is written in the format as used in the research models of the PhD project.

\[
\frac{\Delta x_i}{\Delta p_j} = \frac{\Delta h_i}{\Delta p_j} - x_j \frac{\Delta x_i}{\Delta m}
\]

Where:
- \(x_i\) = quantity of good \(x_i\)
- \(x_j\) = quantity of good \(x_j\)
- \(p_j\) = price of good \(x_j\)
- \(h\) = The Hicksian demand for good \(x_i\)
- \(m\) = Income of the consumer

On the left-hand side of equation 4.1 is the total effect (TE); the derivative of the quantity of \(x\) with respect to its price \(p\). The substitution effect (SE), represents how much of the variation is due to finding similar goods or services that could be substituted into the SME’s ICT procurement basket. The substitution effect is obtained from the derivative of the Hicksian demand with regards price \(p\). The second part of the right-hand side of equation 4.1 is the income effect (IE), using a Marshallian demand function, representing how much purchasing power changes as income or endowment varies.

In the Set 1 NetLogo models pre-existing libraries of preference utilisation “primitives” (short sections of code designed to add functionality to a NetLogo simulation) were used in order for the SME agents to make decisions. In the Set 2 this was developed further by effectively coding the Slutsky equation into the algorithm. The Slutsky equation in equation 4.1 inspired the algorithm driving the choice element of the SME agents in the Set 2 models, with the relationships in equation 4.1 providing the relationships between parameters in the Set 2 models. Parameters and endowments were allocated stochastically, within realistic bands derived from data from the Office of National Statistics (ONS) on the demographics of UK SMEs were based upon information from industry experts.
The Slutsky equation was used in the Set 2 Java models to help drive the “choice” element of the simulations. However, the two halves of the equation could not be conducted simultaneously due to the nature of the programming language and the limitations of CPU technology. Therefore, the equation was split into its components, coded separately, the effect due to substitution and income were calculated separately and the sum of the two parts applied to the give the solution for the given time step. The SME agents were modelled as consumers when selecting between the “cloud” and hardware ICT options (normal goods) and the income that the SME agents had was equivalent to revenue provided by a function of ICT expenditure (as a means of production, explained in greater detail later in section 4.7.1).

4.3.5 Hardware Upgrades or “Cloud” Services - Perfect Substitutes?

An indifference curve is the line showing all the combinations of two goods which give a consumer equal utility. In other words, the consumer would be indifferent to these different combinations. Indifference curves for consumers are strongly influenced by the interchangeability of the goods being considered for purchase (R. Blundell, 1988). When combined with a budget constraint line meeting tangentially, indifference curves can be used to calculate the likely basket of goods a consumer (or in this case an ICT Manager of a SME) would select (Tohamy and Mixon, 2004). While “cloud” services and hardware systems can both perform functions for workers that achieve the same user functionality, they do it in such a way that would not make them perfectly interchangeable. A primary example could be the use of a spreadsheet software package. The ICT Manager has the option of upgrading the users’ laptops and the on premises server to provide the extra processing power, communications and storage required for users to share and work on large spreadsheet documents simultaneously across remote locations, or the ICT Manager could purchase a virtualised “cloud” service where a third party provides access to the firm’s employees to datacentres allowing them to achieve the same result without upgrading their existing hardware (Himura and Yasuda, 2015). This second option also means that the SME has a service level agreement and the third party is responsible for managing the “uptime” of the service; providing the infrastructure and the electricity supply, factors that would otherwise would have to be managed by the SME’s ICT Manager (Johnston et al, 2010). This is essentially the scenario conceived when comparing the “hardware” versus “cloud” options in the simulations.
4.3.6 Marginal Rate of Substitution

The models needed to consider the marginal rate of substitution (MRS). This is an observable phenomenon in microeconomics where the rate of consumption of a good or service is related to the existing endowment; the more of a good a consumer already has the less they value the purchase of more, i.e. the less “utility” they will derive from more of that good and the additional marginal utility will trend towards zero (Balduzzi and Tong, 2004). This concept was integrated into the Set 2 Java models with respect to the purchase of hardware. It was assumed that the MRS would trend towards zero, it also meant that as more hardware was purchased there was a corresponding increase in the relative value of a “cloud” purchase. Hence the use of Cobb-Douglas preferences could be applied to the SME agent algorithm to calculate the value of the hardware and “cloud” services budgets of the SME. This concept is explained in greater detail later in the methodology in section 4.7.1.

4.3.7 A common definition of a Software Agent

The flow diagram in figure 4.3, is a generic definition of a software agent of the type used in the Set 1 models, designed to maximise its utility. For an agent based model to simulate the behaviour of a society the elements it needs to include are self-sufficiency in decision-making (autonomy) and the ability to “remember” what has occurred in previous time steps (Bresciani, P et al, 2004). Generally, the events of the previous time step inform the outcome of the current time step. The term “sensors” in figure 4.2 reflects that the agent can observe its environment and the behaviour of other agents in the system.

In the early Set 1 test models conducted in NetLogo both the SMEs and ICT Providers were constructed as agents that could interact in “money space” and their locations on the x and y-axis represented their expenditure/investment on either “cloud” or hardware ICT respectively (explained in more detail in section 4.6.4). These were based on simple generic agents with endowments of money and cost structures. A random number generator was used to specify the starting budgets of the SMEs per user within upper and lower limits taken from interviews from industry experts and across a Gaussian distribution.
4.4 Use of Markov Chains in the Models

One of the principles applied to the models of both Set 1 and 2 was that of Markov Chains, where the probabilities of events are calculated from given starting points with the outcome of that event used for the starting point of the next time step’s event. The example Markov Chain in Figure 4.4 shows diagrammatically the progression of a series of events starting at $S_0$ and ending at $S_7$. The different pathways from starting point and the end point are represented by the nodes and branches of the network in the diagram. The path taken over time varies in probability and this is shown on the branches of the nodes ($S_0$ through to $S_7$). The progression of the software agents in the Set 1 and Set 2 models do the same (with respect to time). The outcome of the simulation is in part defined by the weighting and the probabilities of the parameters and events the SME agents encounter over the time steps they experience. Therefore, care was taken in the determination of the parameters, their relative weighting and their realistic probabilities. Markov Chains are routinely used in agent based models and can help to produce statistically significant results (when used correctly) (Snijders et al, 2010). As discussed in the results chapter 5, the Set 2 models were used to forecast the size of SME ICT budgets in the UK and the result produced by the model was close to the result found by market survey. This therefore confirms that Markov Chains were used correctly in the Set 2 models.
The next section of this chapter discusses the parameters used in the Set 1 models.

4.5 Desirable Parameters to Model: Set 1

Often a key feature of an ICT manager’s role is to provide reliable and secure computing facilities to their users. Many organisations have become critically linked to their usage of ICT to perform their business functions (Brown and Lockett, 2004). Therefore, the price of ICT is often of secondary importance after reliability and security. The list and hierarchy of parameters, used in the model, was developed after studying academic and industry material around ICT procurement. The knowledge gained from semi-structured interviews with industry experts was given the highest ranking in terms of importance.

In particular there were three experts who provided a great deal of support, they did however ask not to be identified and referred to as J, N and S. What follows is a brief description of their positions in the industry and why their insight was useful.

- J works as senior system architect for a leading ICT provider with a broad range high security clients including dozens of SMEs as well as large enterprises. He is well positioned to understand the latest technology and has a large cross section of clients, his job involves listening to his client requirements, where he is exposed to understanding their concerns over “cloud” security and their per
user budget constraints. J is also a regular attendee of conferences where he is exposed to significant number of peers who discuss ICT issues in forums.

- N is an ICT manager at a local authority with ICT user requirements very similar to those of an SME, particularly at a per user level. He has similar requirements on utility and his budget constraints are also similar. He attends conferences and spends a lot of time with peers sharing “best practice”.

- S is a senior ICT manager at a large insurance company, he has recently project managed a large system migration to a new “hybrid cloud” solution – where they are using “cloud” technology and virtualised servers, but on a system platform wholly owned by the insurance company he works for rather than an outsourced provider. This is a growing market trend in ICT provision and can be considered as the crossing point between the hardware and “cloud” budgets. S’s input proved valuable as he could give a great deal of insight as to how his company selected the ICT firm that was to provide them with the technology they purchased. This information is used in this thesis to help develop the Set 2 models, in particular Model B where there are ICT provider agents present.

In the first stage of the Set 1 NetLogo model the security and reliability of hardware as well as consumer perception could be combined in a single parameter referred to as “trust”. The greater the trust a client has in the goods or service they are procuring the more they are willing to pay for it. In the Set 1 models the budget allocation between “cloud” and hardware was calculated using a set of preferences listed in table 4.1. These preferences were randomly allocated to each SME agent using Gaussian distributions. In turn these distributions were modified to reflect real life data gathered.

The ICT industry, along with others, observes a phenomenon that can be referred to as “lock-in”. This is where the market players standardise on technologies or specifications because a significant number of users have already bought into it. For example USB connection technology or the DVD-rom are now effectively universal across the industry. This effect is far easier to model using agent based models that have software agents which can observe the decisions of their peers, and hence simulate the “lock-in” effect more effectively. This was incorporated in the Set 2 models where there was a provision where the SME agents could choose to follow the average spending pattern. The effect of 'lock-in" was modelled into the Set 1 models using a random parameter with a normal distribution where there was a probability between 0.7 and 1 that the SME would keep the exact same spending pattern as the previous time step. This
The per unit cost parameter of "cloud" services in the simulations was taken from sampling the market in 2015.

The next section of this chapter discusses a decision matrix of parameters important to ICT decision makers in UK SMEs. This was used to inform the design of the parameters and their relative weighting in the final Set 1 models.

4.5.1 Relationships in the Market

As discussed in Chapter 2, the government can apply legislation in the form of taxes, incentives and regulations. The government in turn are voted into power and should appease an electorate to get re-elected. Within the electorate there may be environmental activists who apply political pressure on the government to make the ICT market more energy efficient in its goods and services. These relationships in the economy were determined from interviews with the 3 previously mentioned ICT industry experts and executives at HP and have been drawn out in a relationship map in Figure 4.5. This map guides the creation of the algorithm behind the simulations. This relationship map shows where market players interact with one another and where information can be exchanged, thus resulting in pressure being applied. These pressures can result in price changes or changes in the composition in the offerings provided by ICT suppliers or even changes in demand by client firms.
Figure 4.5: Schematic diagram representing how the different elements of the economy interact with each other when relating to the procurement of ICT services, author’s own. The arrows represent information exchanges that can lead to influence.

The relationship map shown in Figure 4.5 was the first draft, based upon market analysis provided by ICT industry experts. However, it proved difficult to code in NetLogo (the platform used to produce the Set 1 models). As the priority in the original Set 1 models was to prove the concept of using agent based models for analysing environmental policy and the ICT market it was possible to use a simplified relationship map (shown in Figure 4.6) to achieve this. There was the potential to grow the Set 1 model’s complexity as required, rather than beginning with a complicated model which could have caused difficulty identifying and resolving errors. This would have involved a lengthy process of reverse elimination of parameters and agents. The first NetLogo models were directly formed from the relationships described by the map in Figure 4.6.
In the relationship map represented in Figure 4.6 exchanges between the agents are financial and hence the agents are operating in an information space (akin to money space in the sense that the physical location of the agents is not modelled). Therefore, the model observes their financial transactions and exchanges of information, rather than movements in geographical space. However, even though exchanges are financial there can be non-financial pressure applied to other agents. For example, policy makers will have political pressure placed on them by environmentalists to give targets to rest of industry to reduce their greenhouse gas emissions (GHGs). The policy makers then have the power to create legal targets or taxes that influence the free market to alter its behaviour and follow an economy that is less GHG emitting. In the Set 1 NetLogo model the location of the agents at the end of their decision-making process represents their choice, explained in greater detail in the discussion of "money space" in section 4.6.4.

In the relationship map shown in Figure 4.6 the ICT companies and their clients are both simultaneously affected by the policies created by the policy makers. Even if a policy is aimed at just the ICT companies they will respond in such a way that is likely to have a knock-on effect on their clients and vice versa by often passing costs onto clients. In a
similar way, the shareholders of the client firms can promote an indirect pressure upon
the ICT managers to conduct themselves in a manner that results in maximised profits.
However, it could be that the shareholders expect the firm to minimise its GHG
emissions to meet targets on corporate environmental responsibility. Meeting these
targets can also be part of a programme to reduce energy costs and therefore improve
the financial performance of the company (Hatakeda et al, 2012).

ICT managers can use reverse auctions (a method of putting contracts out to tender
where companies are invited to offer the lowest price for a contract while meeting all
the service and hardware requirements specified) as well as direct negotiations.
Reverse auctions are often used in public service tenders and they have the added
advantage of increasing the clarity of the procurement process. A similar principle was
applied to the Set 1 model where the price of the ICT providers’ offerings is required to
drop below a threshold level before a purchase is made.

4.5.2 Why use NetLogo in the Set 1 Models?

NetLogo 5.05 was selected as the platform for generating the first generation Set 1 client
agent models after trials with writing ABMs in Java using libraries. It was a valuable
learning exercise and allowed the author to develop knowledge as to how algorithm
design is converted into usable code for simulation. It was found that NetLogo was
quicker, partly because of the use of “primitives” (short cut commands that instruct the
agents in commonly requested behaviours) and partly because of the graphical user
interface that made it easier and quicker to generate pictorial results simultaneously
with numerical data (Grimm and Railsbeck 2012).

4.6 Set 1: A NetLogo model in practice

In preparing the model for research work, several different avenues were investigated.
The first step was to examine what were the most salient parameters and how they
interacted with each other. These parameters were selected by interviewing industry
experts and by examining academic material. This developed into a relationship map
where the interactions between key participants in the ICT market place are
summarised and shown pictorially in Figure 4.6. This is a far simpler relationship map
than the one shown in Figure 4.5 and was used to generate the client agent simulation in NetLogo. An important lesson learnt in the development of these models is that ABMs do not need to model an entire economy to be useful in calculating results or producing emergent behaviour. It is more important that the agents store information from one time step to the next, to provide emergent behaviour and allow trends to be examined.

The primary aim of developing the Set 1 models in NetLogo 5.0.5 was to test the viability of examining the effects of environmental policy on ICT procurement using software agents, aiming to answer the first research question of the thesis. The secondary aim was calculating the response of the client procurement of ICT hardware or “cloud” services to varying carbon tax levels. Ultimately the final aim was to build a series of models of increasing complexity and accuracy, accepting real life data and producing forecasts that could be used for predictive policy analysis.

The initial process of determining the most important factors of ICT procurement was based upon business economic principles (gained from a literature review) and practical knowledge of the industry (gained from observation and semi structured interviews with contacts within the ICT industry). The focus was on visualising what an ICT manager at a client firm would prioritise in their purchase of ICT hardware or services. These factors became the parameters within the model discussed in table 4.1.

### 4.6.1 Decision Matrix for ICT Managers (SME agents)

Table 4.1 shows the decision matrix used for the SME agents used to summarise the parameters important to ICT managers at client firms. The information for the decision matrix was gained after interviewing executives and engineers at HP and by interviewing industry experts. The parameters in the decision matrix were then used to design the algorithm that ran the simulations in the research and were ultimately used to instruct the SME agents in the Set 1 model.
Table 4.1: A decision matrix table listing parameters that of interest to SMEs selecting an ICT product or service designed to aid employee productivity.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Yes / No (On / Off)</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>How many users are there?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>What is the budget available per user?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Do they use managed facilities?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Does the client or the facility pay the facility's overheads?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Is there a requirement for remote working?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Is there a requirement for a storage area network and/or remote backing?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Does the firm have any hardware or software legacy issues?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Is there a requirement to have sole control of data?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Do Key Performance Indicators (KPIs) include total life cost performance?</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the process of selecting the factors in Table 4.1 there was a need to consider how market players in the real world interact with each other. For example, ICT companies that operate across the European Union usually have shareholders who own the company and expect the management to maximise profits. In general results are published quarterly and this puts pressure on management to achieve short term results and gains (Gillan and Starks, 2000). This pressure dictates much of the behaviour of the ICT companies, the composition of goods and services offered and their pricing. The presence of competing ICT companies also affects the pricing as players vie for market share. Demands from clients (who often have shareholders themselves) also affect the way the market players (ICT companies, clients, government, etc.) – interact. Within the ICT companies they are likely to have data centre managers who provide the “cloud” services and must operate with changing overheads and possibly legislation (data management, power consumption, etc.). The parameters of the decision matrix in Table 4.1 migrated into the parameters seen in the algorithm, for example they were highly relevant in affecting the values of the preferences used in the algorithm as a total weighted preference of hardware and “cloud” solutions. Put in other words, the preferences seen later in the Set 1 and Set 2 algorithms were an amalgam of for example “how many users are there?”, “is there a requirement for a storage area network and/or remote backing?” with “Do Key Performance Indicators (KPIs) include total life cost performance?” and all the other questions in the decision matrix except “Does the firm have any hardware or software legacy issues?”, which became the Legacy
parameter in the Set 1 and Set 2 models and the question “what is the available budget per user” became the budget constraint in the Set 1 models.

4.6.2 Assumptions and calculations in the Set 1 Models:

One of the first assumptions in this simulation is that the total monthly budget that the client has is spent on either hardware or “cloud” services. This is analogous to real life behaviour where many procurement decision makers spend their full budget allocations in order to avoid the possibility of it being reduced in future. This is especially true if savings are not accounted for in key performance indicators. This is similar to constrained optimisation problems in economics (Chiang, A. 1996) and was treated as such in the methodology. This therefore means that money spent by the client firms on hardware is not available to spend on “cloud” services.

In this model, the assumption is that the primary concern of the ICT procurement decision maker is to maximise the provision of ICT services. This involves a combination of functionality, productivity, bandwidth, flexibility and reliability. These factors were tallied together in the simulation under the general headings of “trust-in-hardware” [TiH] and “trust-in-cloud” [TiC], with the assumption that the greatest weighting within these factors would be reliability. The greater the TiH the higher the probability that client agent would spend some of its budget in the time step on hardware. It is important to note that the maximum value that TiH can be is 1 and that even if TiH is equal to 1 that the ICT client agent still has a finite probability for selecting some expenditure on “cloud” services. This is because the model is designed so that the TiC (again limited to a maximum of 1) combined with a function related to “legacy” [LG] controls the probability that some expenditure goes onto “cloud” services.

The decision-making process for an ICT manager (client agent) is often complicated in real life by the need to maintain legacy systems. This was an issue mentioned repeatedly by industry experts interviewed for this thesis. This can be a significant issue for firms needing to maintain historical databases etc. In the Set 1 simulation, there is a variable called “legacy” that varies from 0 to 1. If the legacy is 1 then there is a zero chance of the clients changing their purchasing behaviour as they are 100% committed to the technology that they are already using. However, when the legacy is between 0 and 1 then the “draw” function in NetLogo is applied deciding the next time step outcome is enacted.
The carbon tax used in the model is a proxy for the Climate Change Levy (CCL) and the Carbon Reduction Commitment Energy Efficiency (CRCEE) schemes in the UK. These schemes encourage industry to reduce their greenhouse gas emissions through a combination of increased costs of fossil fuels and increased competitive behaviour. However, we can simplify the way in which the schemes operate by saying that they function in the same way as a straightforward tax on a good discourages its consumption by increasing costs. Therefore, in the simulation the carbon tax \([\text{CarT}]\) is modelled as an increased cost.

The budget available to ICT clients was a random amount along a normal bell distribution. The limits are based on the upper and lower limits of average spending of small to large enterprise per user – this data was given by industry experts. The upper limit was set at £200 per user per time step (set as one month) and the lower limit was set £0 per user per time step. The model was set up so that the ICT clients could have a varying budget over time (within the limits and bell curve), this was to reflect the reality that ICT budgets often fluctuate over time.

4.6.3 Functions in the Set 1 model.

The most critical function within the simulation is the one that determines spending on hardware. The model then assumes that the rest of the monthly budget is spent on “cloud” services so it is a simple subtraction of the hardware spend from the total budget. In the simulation, the budget endowment per user is produced randomly in the first time step; the NetLogo platform has a random number generator that allows the researcher to select the mean, the standard deviation as well as the upper and lower limits. The parameters for the random number primitive generating the initial monthly budget endowment for the SME agents were based upon interviews with professional IT managers.

Therefore, the algorithm controlling the position of the ICT client in the money space of the model is controlled by the following functions.

\[
\text{Client}_y = \text{Budget}_{\text{Client}} \times f(TiH, TiC, LG, \text{CarT})
\]

And

\[
\text{Client}_x = \text{Budget}_{\text{Client}} - |\text{Client}_y|
\]

Where \(\text{Client}_y\) is the amount spent per time step by the client agent on hardware.
Client \_x is the amount spent per time step by the client agent on “cloud” services.

Budget \_\text{Client} is budget available to the client agent during time step \text{t} and is also a random function.

TiH is the “trust in hardware” a composite value indicating the confidence the market has in the reliability, security and usefulness of hardware solutions.

TiC is the “trust in cloud” a composite value indicating the confidence the market has in the reliability, security and usefulness of “cloud” solutions.

LG is the “legacy” function; the closer it is to 1 the more likely the client agent is to repeat the same result as the previous time step.

The position of the client agent in money space represents the amount spent by that agent on hardware and “cloud” services respectively.

### 4.6.4 Money Space

Due to the use of primitives in NetLogo to code the functions discussed earlier, the movements of Client agents on the screen represent the spending pattern of the ICT manager. The position along the x-axis represents the spending on “cloud” services. The further the client agent is along the x-axis the more money is spent on “cloud” services within a time cycle. In this model, this is assumed to be one month (known as a “tick” in NetLogo). Correspondingly the position of the client agent along the y-axis represents the amount of money spent on ICT hardware in the month. In this model, it can be assumed that the ICT hardware is leased and therefore paid for monthly (this is common practice in real life as it allows firms to offset payments against their tax liabilities).

### 4.7 Model A of Set 2: SME Agents and Varying Carbon Tax Levels written in Java

The preceding sections of this chapter discussed the Set 1 models written in NetLogo. The Set 1 models provided a proof of concept for the use of agent based modelling to model the behaviour of ICT companies, answering the first part of the research question of the thesis. From this point on the discussion is on the Set 2 models built in Java.

Creating a bespoke model in Java was more efficient in researching the thesis questions as specific parameters could be modelled directly to give more accurate results. The model was originally intended to be built in the agent modeling platform “MASON”, a series of Java libraries written at George Mason University to further the research work.
of economists and social scientists (Luke et al, 2004). However, these libraries turned out to be too highly optimised to the original research team that developed them. Customising these libraries would have been more complicated than creating models from first principles in Java. Creating the model from first principles enabled the author to ensure that all the required parameters were modelled and that the model was optimised to the research question.

The Set 2 Java models were more realistic than those written in NetLogo as a link was modelled between the revenue of the SME agents and their budgets. In the Set 1 NetLogo models the budgets were set randomly at the start of the simulation and overheads were then varied to discover the emergent behaviour of the system.

In the Set 2 models the SMEs aim to profit maximise and cost minimise while selecting between “cloud” solutions and hardware upgrades. It is assumed that all the firms (to varying degrees) use ICT as a factor of production. It is important to note the variety of SMEs that can exist and that there are different definitions of a SME. For the purposes of this thesis the definition is taken from the EU: a firm with more than 10 employees and less than 250 as well as a revenue less than EUR 250 million per year. This is the same definition used by the UK government.

4.7.1 Cobb-Douglas Production Function as Used in the Set 2 Models

In the process of researching ICT and SME productivity the work of Thomas Hempell of the Centre of European Economic Research was examined. Hempell conducted econometric analysis of the relationship between ICT competence and productivity in Germany in the 1990s (Hempell, T 2002). The use of a Cobb-Douglas production function, for calculating the production output of a firm for given inputs of capital and labour, was critical to Hempell’s work. Therefore, it made intuitive sense to also use the Cobb-Douglas production function in the Set 2 models. In these models the primary algorithm that drives the SME agents used a Cobb-Douglas production function to calculate the amount of production of each SME in each time step. In the Set 2 models the production function (Q) within the algorithm estimates a contribution to the SME’s revenue due to having ICT as a factor of production.
Equation 4.1
The Cobb-Douglas production function in its standard form (Chiang, A 1984):
\[ Y = AK^\alpha L^\beta \]
Where: \( Y \) is the production output of the SME
\( L \) is the level of labour
\( \alpha \) is a positive fraction not equal to 0
\( \beta = 1 - \alpha \)
\( K \) is the amount of capital used by the SME
\( A \) is a constant
The Cobb-Douglas production function assumes that both capital and labour required for production. Special features of the Cobb-Douglas function include that the function is homogenous to \( \beta + \alpha = 1 \). Its isoquants are always negatively sloped and convex for positive values of \( K \) and \( L \).
Hempell replaced the constant \( A \) with a function for ICT capital, discussed later, where \( A = A(ICT_{nt}, E_{nt}, m_{nt}) \). This equation from Hempell’s work is referred to as equation 4.2.

The derivation of equation 4.3 is shown in the next section. Equation 4.3 was converted into an algorithm that calculates the revenue of the individual SME agents for each time step in the model. Which in turn provides the budget for the SME agent to purchase hardware or "cloud" services.

4.7.2 Deriving the SME Production Function used in the Set 2 Models:
The work of Hempell (Hempell, T. 2002) at the European Centre of Economic Research in the area of experience in ICT and productivity of small firms generated an econometric analysis using an extension of the Cobb-Douglas productivity function \( Y = f(L, K) \) where \( Y \) is productivity, \( L \) is labour and \( K \) is capital). In this scenario Hempell treated ICT as a form of capital. However, Hempell was more interested in the effect of experience upon the productivity of the firm and held productivity due to ICT capital as constant. In the models developed for this thesis the reverse is true; experience is held constant and the equation is solved for ICT. It is assumed in this thesis that the UK and Germany are similar enough economies to apply Hempell’s research to the UK. Both the UK and Germany are G8 members with free markets within the EU and open borders. Therefore, the values found by Hempell’s research and referred to in this thesis as equation 4.1 should be adequate as a starting point for the simulations; where:
\[ Y \] is the productivity of the firm (used later to be a proxy of the revenue as all the production of the SME is assumed to be sold into the market at every time step.
A is function for production for ICT, K is the amount of Capital (later the asset value of the SME is used to calculate this), L is amount of Labour (in the models the number of man-hours per quarter was used).

\( \alpha \) and \( \beta \) are coefficients and were found experimentally by Hempell and used in the simulation.

The assumption is made that both the UK and Germany have a significant number of similar sized SMEs in their economies and that both their economies have similar levels of regulation and market freedom.

Equation 4.2, Taken from Hempell's 2002 paper:

\[ A_{nt} = \alpha(ICT_{nt}, E_{nt}, m_{nt}) \]

Where:

- \( A_{nt} \) is the endowment of ICT in the SME\(_{nt} \) for the time step
- \( A \) is a function taken from Hempell’s 2002 paper equation that takes the ICT capital expenditure and estimates its contribution to the SME’s productivity.
- \( E_{nt} \) is the ICT experience of the SME, in the case of these simulations the experience is held constant and assumed to be equal across all the SMEs.
- \( m_{nt} \) is the constant used by Hempell to hold fixed all the unknown factors in the economy affecting the SMEs.

The equation driving the core simulation, i.e. the productivity of the SMEs eventually grew in complexity until it took the form of Equation 4.3

Taking Hempell’s original premise that we can use the Cobb-Douglas production function for econometric analysis of SMEs (Hempell, T 2002):

\[ \text{SME}_{n} \text{ Product} = f(K, ICT, L) \]

Where \( f \) is a Cobb-Douglas type production function

- ICT is the ICT capital of the SME
- K represents all Capital used by the SME that is not ICT
- L represents Labour working at the SME

\[ \text{SME}_{n} \text{ Product}_t = F(A_{nt} K_{nt}^{\alpha}, L_{nt}^{\beta}) \]

Where \( F \) is the Cobb-Douglas function for the SME \( n \) in time step \( t \)

Where \( \text{SME}_{n} \text{ Product} \) is the income generated by \( \text{SME}_{n} \) \( t \) is the time step, \( t = 0, 1, 2, 3, \ldots \) Limit \( n \) and \( t \) are integer values
\( \alpha = \text{coefficient for } K \text{ (capital)} \)
\( \beta = \text{coefficient for } L \text{ (labour)} \)
\( A_{nt} = \text{is a function of ICT capital of the SME agent } n \text{ at time step } t \)

Taking the natural log of both sides of the equation gives:

\[
\ln SME \text{Product}_{nt} = \ln A_{nt} + \alpha \ln K_{nt} + \beta \ln L_{nt} + C
\]

Where \( C \) is a constant

Substituting for \( A \) using Equation 4.1 gives

\[
SME_{nt} \text{ Product} = F(A(ICT_{nt}, E_{nt}, m_{nt}), K_{nt}^\alpha, L_{nt}^\beta)
\]

Taking the natural log of both sides gives:

Equation 4.3

\[
\ln SME \text{ Product}_{nt} = \alpha \ln K_{nt} + \beta \ln L_{nt} + \gamma \ln ICT_{nt-1} + C'
\]

Where \( \ln SME \text{ Product}_{nt} \) is the natural log of the income of the SME\(_n\) at time step \( t \). Equation 4.3 takes the ICT endowment from the previous time step to calculate the current time step’s SME revenue. The natural log is taken so that the equation 4.2 is linear and hence easier to program in Java. \( C' \) is a constant and is a product of taking the natural log of both sides of the equation. The values of the coefficients \( \alpha, \beta, \) and \( \gamma \) were drawn from Hempell’s experimental results.

\( \gamma \ln ICT_{nt-1} \) can be replaced with \( \gamma \ln (ICT_{\text{Cloudnt-1}} + ICT_{\text{Hardwarent-1}}) \)

to give equation 4.4, the Adapted Hempell equation as used by the algorithm driving the Set 2 models. Where \( ICT_{\text{Cloudnt-1}} \) is equal to the “cloud” services budget for SME\(_n\) from the previous time step and was calculated using the Cobb-Douglas preferences discussed later in this chapter in section 4.8.1. \( ICT_{\text{Hardwarent-1}} \) is the hardware budget of SME\(_n\) from the previous time step, calculated using the equation found in section 4.8.1.

Equation 4.4

\[
\ln Y_{SMEnt} = \ln (ICT_{\text{Cloudnt-1}} + ICT_{\text{Hardwarent-1}}) + 0.686 \ln L_{SMEnt} + 0.189 \ln K_{SMEnt} + C''
\]

It useful to note that this form of the Cobb-Douglas production function is especially useful for econometric analysis because of the way the data sets are handled and the relationships are cross referenced in most econometric software packages (e.g. Stata,
eViews). Its value must be above zero in the simulation for at least 4 time steps for the firm to remain in the market place. Otherwise the agent is removed from the simulation. Much in the same way that agents “die” in Axtell and Epstein’s Sugarscape when they do not have enough resources, SME agents are removed from the model when they are no longer making returns on ICT investment. In this thesis, it is assumed the SMEs in the model all rely on ICT infrastructure to be competitive. This is not to say that SMEs in real life need to have ICT infrastructure to be competitive, but firms that do not are not reflected in these models, and do not need to be for the simulations to be useful in analysing the potential influences of carbon taxes. Within the early Set 2 model iterations, the other factors (excluding ICT) affecting the SME are held constant and can be aggregated into a new single parameter. This could be called business acumen ($B_3$) for example.

Equation 4.3 is the production function utilised by the algorithm in the Set 2 models to simulate the output of the SME agents each time step. It could be regarded that the simulations run a “reduced form’ of the market model as a full economic model would have the demand function of the market in place to determine the market clearing. In these simulations the assumption is that prices remain fixed and the full output of the SME agents is cleared by the market, therefore in the Set 2 simulations output is equal to revenue. This was originally as an interim stage, with the intention to add a demand function later. Results obtained from Set 2 A and B models appeared to mirror reality sufficiently (possibly because inflation in the UK had been low enough not to effect results drawn from data from 2014/15) in order to draw conclusions. This issue is covered more fully in the discussion in Chapter 5.

In equation 4.3 ICT competence is held constant in the Set 2 models and ICT investment affects productivity. In future work it would be of value to observe the effects of varying the level of experience in a manner akin to Hempell’s work. Part of the basis of the assumption of fixed experience levels in ICT usage was that all the SME agents in the model all have ICT managers and it can be assumed that the presence of ICT manager provides a minimum standard across the firm. As the system is in silico and factors that are not in the model are able to be held constant and therefore can be effectively ignored and replaced by new aggregated constant in the algorithm (Dyrstad et al, 1999). Therefore the models are only able to observe the effects of variables that change in the system. In future work it would be of interest to utilise these coefficients and
incorporate further detail into the models. For instance; future work could add in the variable of innovation or experience into the models.

In this thesis's simulation, the author is more interested in the change in productivity and, in turn, profitability of the SME with respect to ICT investment choices rather than the absolute values. It is assumed that ICT investment will occur until \( \Delta \Pi = 0 \), where \( \Pi \) is the profit of the firm. This corresponds to the assumptions based on the principles of neoclassic microeconomics of firms, that there are diminishing marginal rates of return on investment and that the SMEs are cost minimising.

The model exists in an information space – where the agents read each other’s public information, use their own endowments and trade. In early iterations of the Set 2 model the trade was a simple investment by the SMEs into either “cloud” computing, hardware or a combination of the two. The endowments are the budgets available for use per user; endowments can change per time step. It is important to note that in the Set 2 model there is a certain amount of information sharing between SME agents as to how they spend on ICT. This is similar to real life where ICT managers attend courses, discuss how they have solved problems, or even move from firm to firm carrying with them their experiences. This builds to a peer resolved “best practice” and it is possible given the right circumstances for a particular basket of goods to become seen as practically standard best practice.

The results generated by the simulations estimate the spending figures on “cloud” and hardware for each of the individual SME agents and the aggregated figures. These results were then tested for the effects of altering the level of carbon tax on electricity production – analogous to the Climate Change Levy (CCL) applied in the UK. The carbon tax increases the cost of electricity produced using fossil fuels. In the UK, the rate is applied to businesses per kWh used and increases most tax years (0.554p per kWh in 2015 and 0.559 per kWh in 2016). SMEs can apply for Climate Change Agreements (CCAs) where they reduce their liability to the CCL. SMEs can apply for CCAs by getting their energy consumption (including electricity) benchmarked and if they are able to demonstrate planned and/or actual energy reductions they are able to receive CCAs which help to subsidise the cost of their increased efficiency. With respect to this model it is also of interest to see how high the CCL would have to be, to produce a mass shift of SMEs to “cloud” computing and reduce their energy consumption – assuming that “cloud” solutions are more energy efficient for the same level of ICT productivity.
In the flow diagram Figure 4.7 the order of actions taken, starting from the opening parameters, by the simulation with respect to the SME agents is shown schematically. It shows the key point at which the SME agent must observe their environment, check their endowments and produce decisions. One full loop of the cycle represents one time step. Some elements of the process are randomised using a Gaussian distribution around a mean. The means are calculated from real life cost structures. For example, the average cost of commercial electricity or the average budget spent per user were gathered from Office of National Statistics and the Confederation of British Industry. Figure 4.7, repeated from the start of the chapter for clarity, shows schematically what is occurring in the Pseudo code (placed in the appendix of this thesis).

Figure 4.7: Graphical Visualisation of the Algorithm (repeated for clarity) used to model SME agents and ICT Provider agents interacting, schematic author’s own.
4.8 Model B of Set 2: SME agents and ICT Provider Agents written in Java

In Model A of Set 2 only the SMEs have agents. In Model B of Set 2 both SME agents and ICT providers are active agents. The SME agents are active agents selecting between "cloud" providers and hardware providers. The ICT providers (both "cloud" and hardware) are active agents and react/operate simultaneously to each other and market conditions.

It is assumed in this model that the SMEs obey the Cobb-Douglas function of production, discussed in section 4.7.1. The marginal rate of substitution is non-linear and expected to demonstrate diminishing rates of substitution.

The SME agents are modeling small firms and the assumption is that the ICT products and services they use are a factor of their production and vital to their market competitiveness. It is also assumed that the ICT facilities they use consume electricity and are subject to depreciation. At this point it is assumed that the depreciation is constant and linear. However, it would be possible at a later stage to observe what would happen if it were non-linear and inconsistent in its depreciation. In real life ICT equipment can rapidly and unpredictably become out-of-date as technological progression can disrupt market competitiveness very quickly. For example, if SMEs that utilise teleconference facilities quickly and efficiently can save a lot of money from their overheads and allow them to meet their clients on a cost effective virtual platform. Teleconferencing can be very useful for maintaining control on projects or training customers.

The SME agents can be thought of as the IT manager selecting between choices provided by a number of ICT providers. These bundles that they are selecting between are a cross-section of options from exclusively “cloud” services on thin client PCs to exclusively hardware.

4.8.1 Determining the Rate of Substitution between “Cloud” and Hardware Installations (Using Cobb-Douglas Preferences).

What follows is a brief description of Cobb-Douglas preferences as used by the Set 2 models (both A and B).
Using the following mathematical proof, we determine that the marginal rate of substitution between hardware and cloud systems is equal to the relative preference of hardware divided by the relative preference for cloud systems.

**Equation 4.5:**

\[ U(\text{Cloud}, \text{Hardware}) = \text{Cloud}^\alpha \cdot \text{Hardware}^\beta \]

Where \( U \) is utility and \( \alpha \) is “trust in cloud” (equivalent to preference), \( \beta \) is trust in hardware (equivalent to preference). Cloud is the quantity of “cloud” services consumed in the time period in user hours. Hardware is the amount of ICT hardware procured in the time step, again in user hours.

Applying the rules of indices:

Marginal \( U(\text{Cloud}) = \alpha \text{Cloud}^{\alpha - 1} \cdot \text{Hardware}^\beta \)

The Marginal Rate of Substitution = \( \frac{-\alpha \text{Hardware}}{\beta \text{Cloud}} \)

Therefore, the Consumer (SME) Optimal Bundle:

\[ \text{Hardware} = \frac{\beta \times \text{Price of Cloud} \times \text{Cloud}}{\alpha \times \text{Price of Hardware}} \]

\[ \text{Price of Cloud} \times \text{Cloud} = \frac{\alpha}{\beta} \times \text{Price of Hardware} \times \text{Hardware} \]

Price of Hardware \( \times \) Hardware = Hardware Budget

\( \therefore \) Cloud Budget = \( \frac{\alpha}{\beta} \times \) Hardware Budget

The Hardware budget for the individual SMEs is calculated from their productivity – taking the average proportion for ICT expenditure for UK SMEs (based on 2014 statistics).

### 4.8.2 Factors Considered in the Set 2 Models

Table 4.2 shows the factors considered for the SME agents and Table 4.3 the factors considered for the ICT provider agents.

**Table 4.2: The factors considered in preparing the simulation for the SME agents and their corresponding descriptions.**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profit</td>
<td>The SME aims to make a profit. Profit here is defined as: Total Revenue – Total Overheads. Firms that do not make a profit were removed from the simulation.</td>
</tr>
<tr>
<td>Revenue/</td>
<td>Total income; in this model – where, all else is held constant, revenue is a</td>
</tr>
<tr>
<td><strong>Productivity</strong></td>
<td>function of ICT investment. It is assumed that there is a Cobb-Douglas type relationship between Labour and ICT (holding all other capital investment constant). This is because it is assumed that the productivity of the users is improved by efficient use of Information Technology. This was a premise of Hempell's (Hempell, T 2002)</td>
</tr>
<tr>
<td><strong>Budget Per User</strong></td>
<td>The amount of money available to the decision makers in the SME per quarter for ICT investment and maintenance. This parameter was drawn from information given by industry experts. Many ICT manager are given a budget per user. This parameter was variable around a mean with a bell distribution in the simulations (Set 1 and Set 2). The mean level was found after data from the ONS was cross examined (average spend per SME divided by the average number of employees).</td>
</tr>
<tr>
<td><strong>Rate of Depreciation</strong></td>
<td>The rate of effective loss of ICT hardware and usability. It is also designed to consider the rate at which the software and hardware used by the SME may be becoming out of date. If enough of the ICT becomes obsolete the SME is no longer competitive and is therefore forced out of the market. Depreciation is a cost affecting the profitability of the SME and is calculated as an overhead. This parameter affects the profit of the SME and was selected as a parameter after discussions with industry experts.</td>
</tr>
<tr>
<td><strong>Marginal Rate of Return</strong></td>
<td>The rate at which productivity improves as investment into ICT increases this can vary between SMEs. It is assumed that there are diminishing marginal rates of return on investment as a user can only effectively use one device at a time. In this model, it is assumed that the SME invests in ICT until its marginal rate of return is 0.</td>
</tr>
<tr>
<td><strong>Marginal Rate of Substitution</strong></td>
<td>In the market modelled the SMEs are choosing to invest in either “cloud” services or hardware (over and above the maintenance costs of what they have already invested in). This parameter considers how much the SME can substitute the “cloud” service as a replacement for purchasing new hardware. There are diminishing rates of substitution (using the Slutsky equation) considering that “cloud” services and new hardware are not perfectly substitutable for each other.</td>
</tr>
<tr>
<td><strong>Security Level</strong></td>
<td>This parameter considers the level of security the SME requires. If a 100% secure system is required then the users operate in a closed system (that does not interact with the internet or provides teleconferencing) and only use new hardware.</td>
</tr>
<tr>
<td><strong>Service Level Agreement (SLA)</strong></td>
<td>The SME is likely to have either an internal or external supplier of ICT management and as such expect them to provide users at the firm with reliable service. A SLA will give the amount of “uptime” that the SME can expect from its ICT solution.</td>
</tr>
</tbody>
</table>
Lock-In | This parameter represents the level of reliance the SME has on their existing ICT system set-up.
---|---
SME Overheads | This parameter is a composite of all the costs that face the SMEs, including Carbon Taxes, Labour and Capital. The overheads also include the running costs of the ICT (electricity consumption, etc.) and the depreciation costs of the ICT.
“Trust in Cloud” | The level of trust in “cloud” technology that the decision maker at the SME has in “cloud” technology. The level of trust is affected by the level of investment made by the ICT provider and by the SLA on offer.
“Trust in New Hardware” | The level of trust in new hardware that the decision maker at the SME has in hardware technology. The level of trust is affected by the level of investment made by the ICT provider and by the SLA on offer.

Table 4.3: The factors considered in preparing of the ICT provider agents in the Set 2 model B:

<table>
<thead>
<tr>
<th>ICT Provider Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profit</td>
<td>The ICT provider agent aims to make a positive profit. Profit here is defined as Revenue – Total Overheads. If the ICT provider has negative profits (i.e. running at a loss) for more than 4 time periods in a row, then the ICT provider will leave the market. In this model, each time period is the equivalent to 3 months. When interviewing industry experts and HP executives they were keen to highlight the importance of profit to ICT provider firms.</td>
</tr>
<tr>
<td>Investment in “Cloud” Services</td>
<td>The amount spent within the time period by the ICT provider into research &amp; development and marketing the technology. The probability of making a “Cloud” services sale to a SME agent is positively related to the level of investment.</td>
</tr>
<tr>
<td>Investment in Hardware</td>
<td>The amount spent with in the time period by the ICT Provider agent into research &amp; development and marketing of new hardware technology. The probability of making a new hardware sale to a SME agent is positively related to the level of investment.</td>
</tr>
<tr>
<td>SLA “Cloud”</td>
<td>The Service Level Agreement for “Cloud” services – the percentage of uptime guaranteed by contract that the ICT provider can achieve. This is a function of research and development expenditure.</td>
</tr>
</tbody>
</table>
In the Set 2 simulations conducted for this PhD project it is assumed that both the SMEs and ICT Providers are trying to maximise their profits. Therefore, there is an iterative process in the algorithms built into running the SME and ICT Provider agents that attempts to find the optimum ratio of "cloud" services to hardware.

The SME and ICT providers are operating in an information space within a framework. The agents do not move geographically, but are existing as autonomous decision making entities within an information space. Their decisions are based upon internal tables (based upon the parameters described in tables 4.2 and 4.3) and by the information they gather from the market place and the other agents in the simulation.

In this model when the SME agents decide what ICT services or hardware to purchase they first examine their internal information set. This tells them what their budget per user is, how many users they have and what their priorities are. These parameters can change over time and are re-examined after every time step. In particular, the budget per user and the prioritisation of remote working can vary – just as they do in real life. The users working at the SMEs must maintain their productivity levels; this is represented as the diminishing returns on ICT investment and the depreciation of ICT affects their ability to perform against their competitors. This is either because their hardware is becoming less reliable, has lost the performance edge or is compromised by software bloat and malware.

The results of the simulation are presented graphically in an "information space" where the position of the SME agent on the screen represents its expenditure on the different bundles of ICT hardware and services. The further along the x-axis the greater the proportional expenditure on "cloud" services and the further along the y-axis SME agent icon is the greater the proportional expenditure (from the total per user budget) the SME has spent on the purchase of new ICT hardware.

An important step in the modeling process is to identify the key parameters used by decision makers in SMEs when deciding what options they purchase for their ICT requirements. The next stage of modeling was to determine their hierarchy and establish the order in which events in the model should occur to achieve the most realistic result. The flow chart in Figure 4.7 shows the chain of events pictorially, based on conversations with ICT managers. The flowchart starts at the top left hand corner and operates clockwise, the arrows representing the direction of information within the
system. While the model itself did not have a sublevel of instruction representing the ICT manager, the order in which the final program was written does closely correlate to the order of events depicted in the flowchart Figure 4.7.

4.9 Building the Set 2 models

In the Set 2 models, principles of microeconomics of the firm, i.e. the use of Cobb-Douglas preferences and marginal rates of substitution, are applied to generate the part of the algorithm that determines the budget of the SME for “cloud” solutions versus hardware purchases. The principles of the substitution effect and the preference of consumers are applied in the following way. In principle, it is assumed that the SMEs preferences are based upon the level of trust they have in the two technological choices. In general, it is safe to assume that the trust is largely based on their confidence in the technology working as they expect and when they expect, also the level of security with respect to the access of their information by unauthorised third parties (hackers/blackmailers, etc.)

The SME agents represent 5 million entities in the UK – they employ between 10 and 250 people each and represent £480 billion contribution to the economy in 2015. SMEs are a valuable marketplace for ICT firms equating to around 40 percent of annual sales. It is not necessary to model all 5 million SMEs for the simulations to provide useful results. In this experimental phase, the simulations ran 10,000 representative agents which was more than sufficient to provide emergent behaviour.

The productivity of around 4 million UK based service sector SMEs is largely reliant upon the use of ICT products and services. According to a parliamentary briefing document from 2013 the mean amount spent on ICT by UK SMEs is £16000. Of this £6560 is spent on hardware and the balance spent on a combination of ICT services (such as use of a datacentre), consumables (ink cartridges, paper, etc.), software and training.

The ICT experience levels of the SMEs were held constant and equal across the simulations. The assumption behind this was based upon that all the SMEs in the simulation are 10 employees or larger and would therefore even out the experience levels of users; less experienced users would be trained by more experienced users. The model normalized the calculations to a per user basis which further nullified the
possible effects of varying experience. Therefore, experience is held constant in the simulation as we only need to observe the changes caused by changes in carbon taxes and ICT budgets.

The simulation uses the principles of a Markov Chain simulation (as discussed in section 4.4) which takes the probability of events and then automatically carries the process along the sequence of likely events. For example, the SME creates a budget for the hardware and then, based upon the SME’s marginal rate of substitution, generates the likely “cloud” budget. The initial parameters of the agents in the model are based upon real data sources from the Confederation for British Industry (CBI), UK Parliamentary Office for Statistics and the Office for National Statistics (ONS).

*Figure 4.8: Schematic Flow Chart of the SME agents in Set 2 (with interactive ICT Provider agent in Model B)*

The adapted Hempell formula served as the basis for the simulation; using Java and Eclipse, using the following logic path (also shown in Figure 4.8):

- The SMEs are using ICT equipment and services to be able to complete their business tasks and serve their customers. Therefore, there is a connection between
productivity of the firm, ICT and their income. Hempell examined the link through the lens of ICT experience and productivity – in these simulations the link is made with ICT hardware and services as a form of productive capital and the level ICT experience for the ICT firms is kept constant. All the firms have at least 10 employees and there is the assumption that there is cross training on the ICT equipment and software, evening out variations between individuals. Hence making it possible to hold experience constant and adapt the equation used by Hempel for use in this simulation.

- Using data from the UK Parliamentary Office for statistics on the demographics of SMEs in the UK the average revenue was inserted into the model. A random number generator produced a spectrum of values between pre-set upper and lower limits. The assumption was that there was a normal distribution for the income of SMEs
  - The clear majority of SMEs are between 10 – 49 employees and the simulation’s demographics emulate the real-life demographics of UK SMEs as published by the Office of National Statistics (ONS). The numbers produced have an equal chance of being drawn and the average figure of £330,000 is also the median number (based on ONS data from 2014). There was a second tier of SMEs that averaged £1,500,000, but their occurrence was less frequent and in proportion to the real-life ratios of high value SMEs (Data from ONS). The second tier represented the 200,000 SMEs out of 5.1 million which were significantly larger in both the number of employees – 50 to 249 – and turnover. It was decided, in conjunction with the industry experts consulted during the research phase of this thesis, also that these firms represented a substantial difference in the requirements for ICT equipment and services. They are likely to be heavy users of customer relationship management (CRM) software, servers, laptops, PCs, data warehousing, and would likely more significantly affect the results of spending in the marketplace.
  - The heterogeneity of the SME agents was an important factor in the development of the models, reflecting the real-life composition of the UK’s SMEs.
- The number of SMEs can be varied and the results of actions of each SME is stored between time steps and used at the start of the next time step.
- The adapted Hempel equation (shown in Equation: 4.3 and figure 4.8) produces an estimate for productivity the SME has in that particular time step – a proxy for its revenue. However, it is important to note that the model is designed to simulate events “in silico” where the results observed are designed in isolation of other factors that may be affecting the SMEs. For example, the effects of labour
regulations limiting working hours, which would affect all the agents in the simulation equally therefore negating their effect. All factors not included in the model are deemed as being held constant.

- The revenue calculated in the previous time step is then used to calculate the approximate budget for ICT hardware (based upon an average of 4000 hours per quarter). The costs of the ICT hardware are calculated to include the operational costs – based upon an average of 300W power consumption per PC and that the PCs are switched off when not in use, the level of labour and the per unit cost of electricity (randomly generated between £0.08 to £0.20 per kWh). The unit cost for the “cloud” computing is based upon the entry level “Rackspace” user instance, priced at £0.05 per hour (of use) for a 4GB single core equivalent (which is approximately £24 per quarter per employee).

- To consider the effects of peer influence – a randomised proportion of the SMEs are drawn to emulating the average spending pattern of the SME population. The average being calculated at each time step.

- The level of trust the SMEs have in their hardware and “cloud” solutions is very significant for the simulation. The relative levels of trust determine the marginal rate of substitution (MRS) between the hardware consumption and that of purchasing “cloud” solutions (see proof earlier in the document). Once the simulation has determined the hardware budget for each SME, the simulation (based on the MRS of the individual SME) then calculates the “cloud” budget.

- These combined budgets are then used to determine the level of productivity for the SME with respect ICT capital, holding all other factors constant, using the adapted Hempel equation and the simulation is ready for the next time step.

The final algorithm used for Model B set 2 is the same as Model A in equation 4.3. However, Model B has the addition of ICT provider agents which operate in the way shown in the flowchart in Figure 4.9 below and described afterwards.
Figure 4.9: A schematic diagram that represents the algorithm that controls the ICT Provider agents in Set 2 model B. The diagram should be read clockwise from the top left hand corner.

In Set Model B

1. The ICT provider agents are given an allocated endowment of investment funds that are used to develop their ICT hardware and “cloud” offerings. The price of these considers the investment and overheads of coming to market. The composition of ICT provider agents was based upon the mix of multinational, large and SME ICT provider firms seen in the UK marketplace. To normalise the comparisons, the investment cost was used on a per unit basis. This therefore, excluded the effects of absolute size, reflecting the way in which the market works in real life. The per unit price of offerings from multinationals, large and SME providers tend to broadly similar in price when at a SME/consumer level in Model B.

2. There is a positive relationship between the level of investment and the trust the SME has in the offerings from the ICT provider agent. The higher the level of
trust, the higher the probability that they will purchase either hardware or "cloud" services from the ICT provider agent.

3. In Model B of Set 2 there is a function for service level agreements (SLA) that guarantees the amount of uptime (the percentage of usage time that the user can expect the ICT solution to provide the functionality expected). Again, there is a positive relationship, the higher the value of SLA the higher the probability of a transaction taking place between the ICT provider and SME agent. As default the SLA levels are generated by a normal distribution around a pre-set mean. The mean SLA for hardware was set slightly higher than that of "cloud" services.

4. The amount of money that the SME agent spends with an ICT provider agent is dependent upon the service or goods they purchase and how many users they have. Their budget for hardware and "cloud" services is calculated in the same way as in Model A of Set 2.

5. If the ICT Provider agents fail to make a profit for 4 time periods in a row they vacate the market place. The remaining ICT agents then have an increased probability of winning business. This reflects their increased market share.

Results:

Results were generated from the multiple runs of the simulations as .txt files and scatter plots. The next chapter is a discussion of results found from simulations using models described in this chapter.
Chapter 4 References:


Balduzzi, P & Tong, Y. 2004 Testing heterogeneous-agent models: an alternative aggregation approach Journal of Monetary Economics 369-412


Chiang, A. C 1984. Fundamentals Methods of Mathematical Economics


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Chapter 5: Discussion of Results

5.1. Introduction to Discussion of Results

In this chapter of the thesis the results of the experimental phase are critically discussed and analysed. The Set 1 and Set 2 models of the experimental phases were run repeatedly dozens of times, to confirm the repeatability of the results and their robustness. The parameters were methodically changed in the models to observe emergent behaviours and examine how relationships between the parameters worked. How these patterns and behaviours can be extrapolated to policy effects and the real world is also discussed. The primary concern of the research, as discussed in chapter 3, was to determine whether agent based models could be used to analyse environmental policy and generate forecasts on their outcomes. The secondary focus was to determine how carbon taxes affect procurement behaviour. The use of ICT as a factor of production in the SME agents was key to producing usable results from the Set 2 models and provided further academic interest. The methodology in chapter 4 describes how this was done.

5.2. Discussion of the Set 1 Models

The Set 1 generation of models were written in NetLogo 5.0.5. An advantage of using NetLogo for the preliminary research was that it was an agent-based modeling platform designed for use by social scientists. NetLogo has an emphasis on ease of use, and obtaining usable results from relatively simple instruction sets. Therefore, it was ideal for early testing of the feasibility of using ABMs for carbon tax policy research. Which was the first of the two primary research questions discussed in chapter 3. The simulations developed in the Set 1 models were useful in suggesting that agent based models could be used to research environmental policy. This is largely because, when the values of the carbon tax were great enough the change in behaviour of the SME agents could be seen on screen.

The nature of the simulations means there are a spectrum of results for the given range of parameters, largely due to the presence of random number generators (detailed in the methodology in chapter 4). Over repeated instances of simulation runs, the path
taken by results tended to follow a range within a band of outcomes. This observation was partly due to the high number of SME agents in the simulated system. Changing a single parameter at a time and holding all others constant, in keeping with the empirical method, allowed for application of deductive reasoning and the observation of emergent behaviour.

The primary result is that, as carbon tax increases, there is a migration towards spending on “cloud” services. However, it should be noted that very large increases in carbon taxes were required to achieve a movement in the cluster of client agents towards the “cloud” end of the money space. This corresponds well with anecdotal evidence that many ICT managers prioritise many factors over electricity running costs of their hardware installations.

Below, in Figure 5.1 is an example screenshot of the results produced by simulations run on the Set 1 models. The dense “cloud” on screen is made up of “turtles” (the term used by NetLogo for agent) each one representing an SME choosing between ICT hardware and “cloud” expenditure.

*Figure 5.1: a screenshot of ICT client simulation coded in NetLogo in progress.*

In this diagram the x-axis represents expenditure on “cloud” services and the y-axis expenditure on hardware. As the carbon tax percentage increased a shift in the results
cluster occurred towards expenditure in “cloud” services away from expenditure in hardware. The Set 1 models were therefore able to demonstrate that agent based models can be used to evaluate environmental policies.

A critical point of discussion is whether the assumptions within the design of the functions in the model dictate the progress of the agents in the model too strongly, or whether the assumptions are accurate enough to represent reality: There will always be a concern that there is subjective bias in the model design and model parameters. The most effective way to assess whether this occurred is to carefully validate the models against real world data. This was done with the Set 2 models, when comparing the forecasts from the models to survey results. In the Set 1 model it was difficult to compare the results with real data. The randomised elements in the functions are designed to consider the realistic variability in circumstances and decision-making facing the SME agents. However, in the Set 1 models there was only a limited amount of primary data and the model was designed to generate emergent results from limited initial parameters, in a similar way to the Sugarscape models by Epstein and Axtell where there was a "bottom up" approach. The difficulty in evaluating the model results against real life data is one of the reasons the Set 2 models were developed as they allowed for more comprehensive validation.

One of the advantages in using the NetLogo platform is that it is “processor light,” not requiring a large amount of computing resources and can be effectively run on an average laptop. Therefore, there is great amount in flexibility in running experiments, increasing the number of permutations of the simulation that can run in a limited time frame. The key parameters modeled in the Set 1 NetLogo models are detailed in Table 5.1 below. The table discusses parameter values and results of parameter value changes.

The use of “sliders” as input controls for the parameters in the Set 1 model made it easier to conduct sensitivity analysis. This was necessary to observe the behaviour of the system with the methodical changes in parameter values. Each parameter was adjusted in isolation and the behaviour of the SME agents was observed.
Table 5.1 The key parameters summarised the key parameters, the ranges that they run through and the sensitivity results for the Set 1 model.

<table>
<thead>
<tr>
<th>Key Parameter</th>
<th>Value of Parameter</th>
<th>Results of variation of the parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Budget Per User</td>
<td>The original simulations started with a monthly budget set between £0 - £200 with a bell curve distribution.</td>
<td>As per user budgets were increased, the total amount expended increased proportionally on both hardware and “cloud” services.</td>
</tr>
<tr>
<td>Carbon Tax</td>
<td>The carbon tax started at £0.005 per kWh, the actual tax level of the UK's Climate Change Levy. In the Set 1 model this was programmed in to be 100% = GBP 0.005 per kWh and adjusted by a slider from 0% up to 4000%.</td>
<td>Taxes (greater than 200% were required to produce a significant movement in the centre mass of SME agents in the money space. Taxes above 1000% produced a heavy skewed market with dramatically increased spending “cloud” solutions.</td>
</tr>
<tr>
<td>Trust in Hardware</td>
<td>Initially set at 0.997 representing a very high of trust ICT managers have in hardware solutions. This was representative of information gained from industry experts. The value was dropped to levels as low as 0.5 to observe the effects.</td>
<td>The higher the level of trust in hardware, the greater the resistance the SMEs showed to increased spending in “cloud” computing.</td>
</tr>
<tr>
<td>Trust in “Cloud”</td>
<td>The initial level of trust in “cloud” was set at 0.8 (equivalent to 80% trust levels) to reflect the relative market reluctance seen at the time. Again, this judgement was made after speaking with industry experts. This was</td>
<td>The ratio between the Trust in Hardware and “Trust in cloud” was in practice highly significant to the movement of the centre mass of SME agents on screen. The higher the ratio the greater the carbon tax had to be to change the market response towards “cloud” computing.</td>
</tr>
</tbody>
</table>
A strength of the Set 1 models was that adjustments could be made while the simulation was running this meant that visual observations of results could be made easily and quickly, adding to the sensitivity analysis. It also meant that in future work when demonstrating the Set 1 simulations to policy makers they would be able to observe the effects of carbon taxes quickly and easily.

The “legacy” variable was designed to account for the common requirement of ICT Managers in SMEs to maintain existing systems (which is most often at a cost). For example, for the client SME may need to comply with user or industry requirements (for example many professional groups must maintain 7 years’ worth of archives for legal compliance). It also reflected the significant number of SMEs that have high sunk costs in their ICT platforms (combination of hardware and software packages).

One key drawback discovered with the Set 1 model was that it could become unstable when there were more than three independent parameters in the turtles. It was necessary to use the control panel/observer in effect as a third agent, the first two being the SME and ICT provider agents. This third agent was used to input the value of the carbon tax, in this case as a percentage of the electricity costs. In later Set 2 Java based models this was changed to a per unit cost basis as seen in the UK with the Climate Change Levy (CCL). Inputting data using manual “sliders” or input boxes could prove slow but allowed for accurate sensitivity analysis.

| Legacy | The Legacy parameter was initially set at 0.7 and raised to a 0.95 (indicating that 19/20 SMEs would maintain the same expenditure profile for that month and lowered to 0.1. Again guidance was taken from industry experts. | The higher the value for legacy the less sensitive the simulation became to changes in other parameters. When Legacy was set to 0.95 the market would appear almost static with changes in carbon tax or “trust in cloud”. When legacy was dropped to 0.1 the market responsiveness to changes to carbon tax increased dramatically. |

Software issues with NetLogo 5.0.5 includes its reliance on Java 6 to work and there were compatibility issues when making the models work on newer versions of Mac OSX.
the platform used by the researcher. Once simulations were run, live time graphing was possible and could be useful for sensitivity analysis as it was possible to move an input slider and see the affects instantaneously. The use of “money-space” to represent the outputs of the data had the advantage that it gave pictorial results that allowed for trends to be viewed on screen and interpret the results. The position of the turtles in relation to the axis on screen represented the amount of spending on either “cloud” or hardware solutions and as carbon tax levels were changed there was a corresponding movement in spending of the SME agents.

The use of “money-space” was partly to take advantage of the way NetLogo is written, the coordinates of a turtle can be re-entered into the next time step as values for the parameters in the equations that drive the model. This made for a simpler model design, but meant that would be difficult to add further parameters because of the programming limitations of the NetLogo platform.

5.2.1 Limiting factors to the Set 1 Models

The key limiting factor was that many of the assumptions used in the preparation of the Set 1 models come from industry experts rather than scientific survey of UK SMEs. Therefore there is a danger that the experience of the experts consulted for the thesis may have a skewed view of the marketplace and adversely affect the realism of the model development. Even though one expert interviewed worked for a firm that sold “cloud” computing solutions to the SME market and was well placed to give an overview of the ICT market with respect to SMEs in the UK, there is always the possibility that their experience could be biased. Therefore, a scientifically managed empirical survey of UK SMEs would be necessary to improve the robustness of parameters used for model and thus the results of the Set 1 models.

The Set 1 simulation was designed as a proof of concept to show that it was indeed feasible to use agent based models to observe behavioural change in SME agents as a result of carbon tax changes. The SME agents were kept very simple with neither a production function or a demand function in a market place. They did however, have endowments and decision trees to follow with sets of preferences and budgets per user made available to them. The principle that agent based models can provide results through aggregation and the application of the Markov Chain Monte Carlo principle is fundamental to this thesis. The Set 1 model could be too simplistic to make deep insights
into market behaviour, but were sufficiently involved to demonstrate that agent based models could be used to research the impacts of environmental policy, answering the first question of this thesis discussed in chapter 3.

5.3 Discussion of Set 2 Models

The results of the Set 2 Model A and B simulations were both generated as arrays stored as .txt files and as scatter plots produced as .jpeg files. There were trends noted in the results; as carbon tax increased there were shifts in the spending patterns towards “cloud” ICT budgets, reflecting the results of the Set 1 model. However, the carbon tax had to be increased to at least £0.20 per kWh to see a significant change in the spending behaviour. The results were generated after an extensive methodological approach to the use of the Set 2 models. The parameters in table 5.2 were systematically and individually altered and the output graphs observed. If the levels in trust for “cloud” and hardware were kept approximately constant (they were randomly generated between fixed values which could be adjusted) observations could be made on what would happened as carbon tax was altered. If the relative levels of trust between hardware and “cloud” were close to equal, then the simulation’s price sensitivity increases. Even though the system is stochastic there was repeatability in the pattern of emergent behaviour observed when the initial parameters were the same. This is due to the large number of SME agents in the simulation (10,000). The trends produced by the model included the increased amount of overall spending on both the ICT hardware and “cloud” services when the initial revenue was increased and the shape of the scatter plots tended to follow a familiar convex shape (see Figure 5.1).

When comparing market costs of purchasing a SME level server (Sept 2015) for an office network for a company of 10 or more people, purchasing as hardware worked out at nearly half the price of purchasing the equivalent level of service from a virtual server provided by an external support company; £1000 for a Dell versus a typical £1800 per annum required for the virtual “cloud” server. However, the virtualised server will come with a service level agreement and, probably, instant redeployment if a technical error arises, which therefore, reduces the internal support required by the SME for ICT. It is highly likely that the ability of SMEs to redeploy resources from server and network maintenance, both providing labour savings and increasing the availability of employees to work on income generating activities is likely to be greater that the extra unit cost per hour for the virtual “cloud” external server versus the installed hardware server.
Thereby reversing the opportunity cost that arises from redirecting employee time to fixing problems with a server network.

The peer affected SME agents could be observed in the scatter plots as neat horizontal lines cutting through the mass of plot results, see figure 5.1 and 5.3. They tend towards a mean, largely due to the progression of time steps causing the distance from the mean to decay with each cycle of the algorithm and the fact that the mean itself did not alter much once the model cycled a few times. The mean values of the ICT budgets of the simulation were found early in the time horizon.

In this thesis, it was assumed that ICT could be a form of capital as a means of production, an area of academic novelty with respect to agent based modeling. In the previous chapter, there is an explanation as to how the Cobb-Douglas function was applied using first principles and some coefficients taken from existing research. The constants that were not taken from existing research (Hempell, T. 2002) were found experimentally. The main constant of the equation driving the SME agents’ production function was found using the average income of UK SMEs. Using the principle that ICT can be used a means of production for SMEs it is then possible to calculate a relationship between the amount of ICT services and hardware based on SMEs preferences. However, assumptions had to be made, Hempel (discussed in chapter 4) was examining the SMEs of Germany and it assumed that the construction of both the German and UK economies are similar enough that the coefficients calculated in Hempel’s econometric analysis could be used as a starting point for coefficients in simulations for this thesis (OECD, 2003). The Set 2 models used assumptions based on UK 2014/2015 data from the ONS and quarterly time steps. The assumption is also made that the total output of the SME agents was sold at every time step and hence produced revenue. This revenue could then be used to purchase ICT hardware or services with the assumption that the demand side of the market was perfectly horizontal and static. This issue is discussed in the future work section of the next chapter. It is possible that since the Set 2 model took advantage of coefficients taken from Hempell’s econometric analysis (Hempell, T 2002), where all the SMEs in his data set sold either all or the clear majority of their output, in its construction that this helped to make it more realistic. It was also assumed that the level of inflation in the UK was low enough to allow the model to cycle for a few years and extrapolate usable forecasts. Since, if prices are moving slowly enough, the overall business conditions for the SMEs in the model would be close enough to static, barring a shock to the system, for example, through technology advancement, that the ICT
budgets for hardware and “cloud” solutions could be predicted. This reflected the real state of the market during the period of the PhD research, where inflation was consistently below 2% in UK. If SMEs in the UK were overly price sensitive in their vending then this assumption would be a damaging flaw in the model. This could be counted by adding a demand side to the simulation where SMEs would have to sell their output into a consumer market where pricing would produce market clearing. This would impact on SME revenue and hence their ability to invest into ICT hardware and “cloud” services and is discussed further under future work in Chapter 6.

It could be argued that the lack of a demand function is a potential weakness in the model as only the supply side of the market is currently represented. It could be regarded that the simulations run a “reduced form’ of the market model as a full economic model would have the demand function of the market in place to determine the market clearing. In these simulations the assumption is that prices remain fixed and the full output of the SME agents is cleared by the market, therefore in the Set 2 simulations output is equal to revenue. This was not included in the models within this thesis as the aim was to create working models and observe emergent behaviour in the manner of a “bottom up” agent based model in the style of Epstein and Axtell. Future work could develop the model further to create a demand function for the model to perform market clearing and observe the effects of a more theoretically complete, and arguably realistic, model. It would be interesting to observe the effects of having the SME agents having to sell their output into the market place and being affected by pricing. The fact that the Set 2 models could forecast market demand reasonably accurately was probably due to the inflation rates in the UK being low enough not to adversely affect the model’s predictions.

When the models were run the centre mass of the SME agents tended to cluster towards a fixed shape as the number of time steps was extended in the system (usually 20 or more time steps, see Scatter Plots 5.1-5.3). This shows that the model provided a solution and could be used to calculate forecasts.

Markov Chains in an ABM research context was a driving principle of both the Set 1 and Set 2 models. Using Markov Chains is well established in multiple research areas including that of proteins in biology for example (Abagyan et al, 1994). They are commonly used when interactions can be simplified and aggregated results are valued, as in the algorithms used to drive the Set 1 and Set 2 models in the research phase. The
graphs produced by the simulations produce emergent behaviour analogous to consumers exhibiting marginal rates of substitution and Cobb-Douglas preferences. The asymptotic curvatures observed give confidence that the theory was applied correctly into practice and with success.

Table 5.2 shows the fundamental parameters in the Set 2 models; their values and how they were progressed to observe the relationship between carbon tax levels and the spending pattern of the SMEs – fundamental to the research questions discussed in chapter 3 of this thesis and the primary source of novelty of the research.

**Table 5.2 Summary of parameters in Set 2 Model A, including values and model responses.**

<table>
<thead>
<tr>
<th>Key Parameter</th>
<th>Values of Parameter</th>
<th>Response in Set 2 model A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Budget Per User</td>
<td>The average was taken from ONS data, the average expenditure of SMEs on ICT (2014) divided by the average number of employees.</td>
<td>As budget was increased the SME agents increased their overall spending proportionally. The relationship between the two appeared to be linear.</td>
</tr>
<tr>
<td>Carbon Tax</td>
<td>The carbon tax started at £0.005 per kWh, the actual tax level of the UK's Climate Change Levy. The carbon tax was increased systematically up to £0.20 per kWh.</td>
<td>The higher the tax the greater the overall spending. This is largely due to the price inelasticity of ICT. Hardware spending increased as the SMEs continued to purchase ICT hardware, however the running costs associated with hardware increased in line with the carbon tax increases. The ratio of spending between hardware and “cloud” solutions slightly increased towards “cloud” solutions as carbon taxes increased.</td>
</tr>
<tr>
<td>Price of “Cloud”</td>
<td>The price of “cloud” solutions was initially set at £0.05 per hour. It was assumed that there was 4000 hours per user per quarter.</td>
<td>This was not examined as part of this thesis and was kept constant, but is an area for future work.</td>
</tr>
<tr>
<td>Price of Hardware</td>
<td>The price of hardware was set at £0.086 per hour, this calculated using average server and PC prices for 2014 and 4000 hours of usage per quarter and an average life of 3 years.</td>
<td>This was not examined as part of this thesis and was kept constant, but is an area for future work.</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Trust in “Cloud”</td>
<td>The mean was set at 0.85 at the initial level, based on information from ICT experts, with the maximum confidence level set at 0.997. Trust in “Cloud” was used to determine the marginal rate of substitution by applying the principles of the Cobb-Douglas preferences (as described in Chapter 4)</td>
<td>This parameter was not varied due to variations of other parameters taking priority.</td>
</tr>
<tr>
<td>Trust in Hardware</td>
<td>This was generated using a random number generator, with a normally distributed range based on interviews with industry experts between 0.3 and 1.0 (1.0 representing 100% trust in hardware)</td>
<td>As the range was narrowed to indicated an average higher level of trust in hardware so “cloud” budgets reduced in relative terms if overall budgets increased. This allowed for a sensitivity analysis of the set 2 models by narrowing the trust in hardware band to the higher end of spectrum.</td>
</tr>
<tr>
<td>Average starting capital of SME agents</td>
<td>Taken from ONS data, with the average GBP 300,000 with a normal distribution.</td>
<td>This parameter was kept as a constant within the model.</td>
</tr>
<tr>
<td>Average starting revenue of SME agents</td>
<td>Taken from ONS data with an average of £330,000, with a normal distribution. However 0.3% of the population of SMEs were</td>
<td>In the set 2 models as starting revenue was increased the spending on “cloud” services increased proportionally more than hardware spending. Overall, as the revenue of the SME increased so the</td>
</tr>
<tr>
<td><strong>Peer Effect</strong></td>
<td>A random number (up to half of the SME population) of the SME cohort were selected in each time step to start approaching the average spend on ICT hardware and “cloud” services to reflect those who observe and mimic the behavior of other ICT managers, assuming it to be best practice.</td>
<td>The models show a thick cluster of SMEs approaching the mean.</td>
</tr>
<tr>
<td><strong>Electricity cost</strong></td>
<td>Random distribution between 7-20p per kWh – taken from OFGEM pricing 2014/2015 pricing. The model’s electricity costs were varied using a random distribution to reflect real life scenario.</td>
<td>The increase in carbon tax had to be very high in order to see a corresponding increase electricity prices and change in behaviour.</td>
</tr>
<tr>
<td><strong>Running cost of Hardware</strong></td>
<td>Calculated as per hour cost of PC plus per hour electricity cost. Per hour cost of PC = purchase price/total hours use. Purchase price of £800 for an average PC was taken.</td>
<td>As the carbon increased and therefore the electricity cost, the running cost of hardware would also increase. Carbon taxes had to increase significantly, over GBP 0.15 per kWh to see a sharp shift in the ratio in spending between hardware and “cloud” services.</td>
</tr>
</tbody>
</table>

Given a much higher revenue (average GBP 1.5 million with normal distribution) reflecting real life data. The starting revenue was varied from GBP 200,000 through to 1,200,000 to observe the model’s response. Impact of carbon taxes decreased, so higher taxes were required to see an effect. Once a certain revenue point was reached (approx. GBP 990,000 stating revenue) further increases in starting revenue had no real impact on the overall ICT budget as spending became constrained by the overall amount of labour.
from industry data, based on 40 hours usage per week (6240 hours in 3-year PC lifespan) = 12.8p per hour. As the carbon tax increased in the model so the running cost hardware increased.

<table>
<thead>
<tr>
<th>Marginal rate of substitution</th>
<th>The marginal rate of substitution is a dependent variable calculated using the preference of SMEs for “cloud” and hardware, which were in turn calculated from trust levels of the ICT managers from the SMEs – see Methodology section 4.7.1 for discussion of how Cobb-Douglas preferences were used for the set 2 algorithms.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labour</td>
<td>The curved behavior of the graphs generated by the set 2 models reflects the marginal rate of substitution. This is largely since the algorithm driving the simulation was based on the Slutsky equation.</td>
</tr>
<tr>
<td>Hardware Budget</td>
<td>The range of labour costs was kept constant in the models in line with the expectation that inflation was at a low enough level not to skew the model (reflective of market situation 2014/2015). The random number generator was adjusted to be left hand skewed towards the smaller end of companies (under 49 employees) so that these companies were the majority, reflecting real life statistics.</td>
</tr>
<tr>
<td></td>
<td>Set 2 Models A and B showed different behaviours with respect to hardware budget. The introduction of ICT provider agents affected the outcome of model B,</td>
</tr>
</tbody>
</table>

This was based on salary ranges of SMEs with a starting point of GBP 22500 as a minimum spend (for one employee) multiplied by a random number generator (range 10-249) to represent the number of employees of the SME.

Hardware budget is a dependent variable calculated by the number of employees multiplied by the

Marginal rate of substitution
<table>
<thead>
<tr>
<th><strong>“Cloud” Budget</strong></th>
<th>number of working hours, multiplied by the running cost of hardware</th>
<th>where expenditure on hardware dropped as carbon taxes increased.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total ICT Budget</strong></td>
<td>“Cloud” budget is a dependent variable based on hardware budgets and marginal rate of substitution as explained earlier in the methodology section</td>
<td>In the models the cloud budget increased as starting revenue increased and as production increased. In general, increasing carbon taxes increased the “cloud” budget, unless the starting revenue of the SME was very high (over GBP 990,000)</td>
</tr>
<tr>
<td><strong>Production</strong></td>
<td>Total ICT budget is a dependent variable based on hardware budget + “cloud” budget</td>
<td>In order to see a change in total budget there had to be an increase in starting revenue and/or increase carbon taxes in the SMEs</td>
</tr>
<tr>
<td><strong>Production</strong></td>
<td>Production is a dependent variable using the adapted Hempell equation (equation 4.3) as explained in the methodology section</td>
<td>Production tended to plateau quite quickly in the models after a certain number of time steps and average around 6.9 lnGBP</td>
</tr>
</tbody>
</table>

*Scatter Plot 5.1: Example result from Set 2 Model A Simulation “Cloud” Budget versus lnProduction.*
Scatter Plot 5.2: Example result from Set 2 Model A Simulation Hardware Budget versus InProduction.

Scatter Plot 5.3: Example result of Set 2 Model A Simulation Cloud versus Hardware Budgets.

In the Results Table 5.3 for Set 2 Model A, the results given for Inproduction, “cloud” budget and hardware budget represent the centre mass of the SMEs represented on the scatter plots. The SMEs started with an average of GBP 330,000 at time step zero. The
value for $ln\text{Production}$ is taken from the Hardware v Production plot and the Cloud Budget is the corresponding output for the given level of production at the SME.

Table 5.3: Table of Results for the Set 2 Model A with SME agents and passive ICT providers. Average income for SME agents at the starting point is GBP 330,000.

<table>
<thead>
<tr>
<th>Time Step</th>
<th>Carbon Tax (GBP per kWh)</th>
<th>Productivity (lnGBP)</th>
<th>Cloud Budget (GBP)</th>
<th>Hardware Budget (GBP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1Q</td>
<td>0.005</td>
<td>6.76</td>
<td>2500</td>
<td>7000</td>
</tr>
<tr>
<td>2Q</td>
<td>0.005</td>
<td>6.86</td>
<td>7000</td>
<td>8500</td>
</tr>
<tr>
<td>3Q</td>
<td>0.005</td>
<td>6.90</td>
<td>7000</td>
<td>8600</td>
</tr>
<tr>
<td>4Q</td>
<td>0.005</td>
<td>6.90</td>
<td>6000</td>
<td>10000</td>
</tr>
<tr>
<td>8Q</td>
<td>0.005</td>
<td>6.90</td>
<td>7000</td>
<td>11000</td>
</tr>
<tr>
<td>20Q</td>
<td>0.005</td>
<td>6.90</td>
<td>9000</td>
<td>11000</td>
</tr>
<tr>
<td>40Q</td>
<td>0.005</td>
<td>6.90</td>
<td>9000</td>
<td>11000</td>
</tr>
<tr>
<td>4Q</td>
<td>0.05</td>
<td>6.86</td>
<td>9000</td>
<td>10000</td>
</tr>
<tr>
<td>8Q</td>
<td>0.05</td>
<td>6.90</td>
<td>10000</td>
<td>10000</td>
</tr>
<tr>
<td>20Q</td>
<td>0.05</td>
<td>6.91</td>
<td>9000</td>
<td>10500</td>
</tr>
<tr>
<td>40Q</td>
<td>0.05</td>
<td>6.91</td>
<td>9000</td>
<td>10500</td>
</tr>
<tr>
<td>4Q</td>
<td>0.50</td>
<td>6.86</td>
<td>6500</td>
<td>12000</td>
</tr>
<tr>
<td>8Q</td>
<td>0.50</td>
<td>6.90</td>
<td>9000</td>
<td>12000</td>
</tr>
<tr>
<td>20Q</td>
<td>0.50</td>
<td>6.90</td>
<td>9000</td>
<td>12000</td>
</tr>
<tr>
<td>40Q</td>
<td>0.50</td>
<td>6.90</td>
<td>8000</td>
<td>14000</td>
</tr>
</tbody>
</table>

As the carbon tax increase the total amount spent on ICT increases. As can be seen in Table 5.3. It is interesting to note that the hardware budgets increase as the cost of the carbon tax increases. However, the cost of the hardware in the model considers the electricity costs and therefore the cost of consuming the same amount of hardware increases. It is probably more useful to note that the ratio of “cloud” services versus hardware consumption as the number of time steps increases tended to stabilise as the number quarters increased. After 40 quarters the ratio tended to fix and become unaffected by greater numbers of time steps. Hence as the research progressed each iteration of the model was run from 40 time steps or less.

It is also useful to observe that the relative production associated with ICT stays broadly the same, regardless of the hardware budget. This is because the amount of labour stays the same throughout the modeling process. It was also found that the level of production stabilised in a relatively few time steps. This indicates that the system stabilises relatively quickly. This is another reason why adding a demand function to the model
would be an interesting future development as real life markets rarely stabilise so quickly.

**Results Table 5.4: Table of Results for Set 2 Model A with SME agents and passive ICT providers. Average income for SME agents at the starting point is set at GBP 660,000.**

<table>
<thead>
<tr>
<th>Time Step</th>
<th>Carbon Tax (GBP per kWh)</th>
<th>Productivity (lnGBP)</th>
<th>Cloud Budget (GBP)</th>
<th>Hardware Budget (GBP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4Q</td>
<td>0.005</td>
<td>6.86</td>
<td>10000</td>
<td>11000</td>
</tr>
<tr>
<td>20Q</td>
<td>0.005</td>
<td>6.90</td>
<td>10000</td>
<td>11000</td>
</tr>
<tr>
<td>4Q</td>
<td>0.05</td>
<td>6.89</td>
<td>10000</td>
<td>11000</td>
</tr>
<tr>
<td>40Q</td>
<td>0.05</td>
<td>6.91</td>
<td>10000</td>
<td>11000</td>
</tr>
<tr>
<td>4Q</td>
<td>0.50</td>
<td>6.89</td>
<td>10000</td>
<td>12000</td>
</tr>
<tr>
<td>8Q</td>
<td>0.50</td>
<td>6.90</td>
<td>9000</td>
<td>12000</td>
</tr>
<tr>
<td>20Q</td>
<td>0.50</td>
<td>6.90</td>
<td>10000</td>
<td>12000</td>
</tr>
<tr>
<td>40Q</td>
<td>0.50</td>
<td>6.90</td>
<td>10000</td>
<td>14000</td>
</tr>
</tbody>
</table>

Results Table 5.4 shows the results for the Set 2 Model A with SME agents and passive ICT providers with increased average income of GBP 660,000. The results given for Productivity “cloud” budget and hardware budget represent the centre mass of the SMEs represented on the scatter plots. The SMEs started with an average of GBP 660,000 at time step zero. The production is taken from the Hardware v Production plot and then the “cloud” budget is the corresponding output for the given level of productivity. The “cloud” and hardware budgets do not appear to increase significantly over the previous set of results, this is partly due to the number of employees in SME agents not increasing with increased revenue and the total number of hours worked per quarter does not change. It was interesting to note the increased spread of the SME agents in the scatter plots. Also, the production associated with ICT does not change significantly, again this is most likely because the absolute number of user hours does not change.

**Results Table 5.5: Table of Results for Set 2 Model A with SME agents and passive ICT providers. Average income for SME agents at the starting point is GBP 990,000.**

<table>
<thead>
<tr>
<th>Time Step</th>
<th>Carbon Tax (GBP per kWh)</th>
<th>Productivity (lnGBP)</th>
<th>Cloud Budget (GBP)</th>
<th>Hardware Budget (GBP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4Q</td>
<td>0.005</td>
<td>6.86</td>
<td>10000</td>
<td>11000</td>
</tr>
<tr>
<td>8Q</td>
<td>0.005</td>
<td>6.90</td>
<td>10500</td>
<td>11000</td>
</tr>
<tr>
<td>8Q</td>
<td>0.015</td>
<td>6.90</td>
<td>10500</td>
<td>11000</td>
</tr>
<tr>
<td>8Q</td>
<td>0.50</td>
<td>6.90</td>
<td>11000</td>
<td>11000</td>
</tr>
</tbody>
</table>
Results Table 5.5 shows the results for Set 2 Model A with SME agents and passive ICT providers. The results given for Productivity Cloud Budget and Hardware Budget represent the centre mass of the SMEs represented on the scatter plots. The SMEs started with an average of GBP 990,000 at time step zero. The productivity is taken from the Hardware v Productivity plot and the Cloud Budget is the corresponding output for the given level of productivity.

5.4 Discussion of Results for Set 2 Model B

The insertion of ICT provider agents into the Set 2 model B necessitated the use of a trade algorithm. This trade algorithm used a scoring system for when the ICT agents encountered the SME agents and the SME agent chose whether to purchase hardware, “cloud” services or combination of the two from the ICT provider agent. The parameters affecting the probability of the SME agent's purchase are listed in Table 5.6. There the parameter is listed, why it was selected as a parameter is detailed and the impact it had on the simulation is discussed.

Table 5.6: Summary of key parameters of Set 2 Model B in addition to those in Set 2 Model A (see table 5.2).

<table>
<thead>
<tr>
<th>Key Parameter</th>
<th>Value and Function of Parameter</th>
<th>Response in Set 2 Model B to Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service Level Agreement (SLA)</td>
<td>Service Level Agreement value varied between 0.900-0.999, with a distribution skewed towards the higher end reflecting companies’ tendency to offer higher levels of SLAs. ICT agents each had an endowment of an SLA (with the endowment being dependent on the level of investment of the ICT provider into hardware or “cloud” services; ICT agents had separate SLAs for hardware and “cloud” services), while SME agents each had a requirement. The trade would only occur if the provider (ICT) agent encountering the SME agent had an SLA value higher than the requirement of the SME.</td>
<td>If the SLA requirement of the SME was set lower trades occurred more quickly and the model settled into a steady state more quickly. There were no other noticeable effects of SLA on the model response.</td>
</tr>
<tr>
<td><strong>Profit</strong></td>
<td>Profit is a dependent variable of the ICT agent calculated by total revenue - total overheads. If in the simulation the profit was &lt;0 for 4 consecutive quarters the ICT provider was removed from the market, mimicking the real life scenario of companies leaving a marketplace.</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Revenue</strong></td>
<td>Revenue of the ICT agent is a dependent variable calculated by ((\text{total number of hardware users} \times \text{price per user of hardware}) + (\text{total number of “cloud” users} \times \text{price per user of “cloud” services}))</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Price per user of hardware</strong></td>
<td>Price per user of hardware is a dependent variable calculated by (\frac{\text{Cost of Investment (from published industry data)}/\text{Return on investment time horizon (12 quarters, or 3 years)}/[\text{expectation of number of market users (from industry publication)]} + \text{a margin of a normal distribution of 2-20% for ICT agent (based on industry data from Hewlett Packard)}}}{\text{ICT provider investment into hardware}})</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Price per user of “Cloud” services</strong></td>
<td>Price per user of “cloud” services is a dependent variable calculated by (\frac{\text{Cost of Investment (from published industry data)}/\text{Return on investment time horizon (12 quarters, or 3 years)}/\text{expectation of number of market users (from industry publication)]} + \text{a margin of a normal distribution of 2-20% for ICT agents (based on industry data from Hewlett Packard)}}}{\text{ICT provider investment into hardware}})</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>ICT provider investment into hardware</strong></td>
<td>ICT provider investment into hardware was based on industry information from Hewlett Packard based on a corresponding linear</td>
<td>As the ICT provider investment into hardware increased there was a corresponding linear relationship.</td>
</tr>
</tbody>
</table>
range of USD 1-3 billion (using a random number generator) and converted to GBP by a conversion of USD 1.55 / GBP 1.

increase in the total overall spend by the SME agents.

ICT provider investment into “Cloud” services
ICT provider investment into “cloud” was set using information from the IT industry with a mean value of GBP 300,000,000 (from interview with industry experts) with a +/- margin of 20%, giving a maximum of GBP 360,000,000

As the ICT provider investment into “cloud” Services increased so the SME agent spending on “cloud” services was observed to increased. This was due to the setting in the model that as investment in “cloud” services increased so did trust in “cloud” services

Total ICT investment
Total ICT investment is a dependent variable calculated by ICT provider investment into hardware + ICT provider investment into “cloud” services

N/A

Cost of Hardware Sales
Cost of hardware sales is a dependent variable and was taken from industry information from interviews with experts and incorporated into the model on a per user basis

N/A

Cost of “Cloud” Sales
Cost of “cloud” sales is a dependent variable and was taken from industry information from interviews with experts and incorporated into the model on a per user basis

N/A

ICT provider overheads
ICT provider overheads is a dependent variable calculated by Total ICT Investment + Cost of hardware sales + cost of “cloud” sales

N/A

It is possible that increasing the number of parameters increased the amount of noise into the system, and the corresponding scatter plots do indeed appear to be slightly noisier than those from the previous generation of plots where only the SMEs are agents in the system.
Table 5.7: Summary of Results for SME Agents and ICT Provider Agents Model. Average SME starting revenue GBP 330,000 and 10 ICT Provider agents.

<table>
<thead>
<tr>
<th>Time Step</th>
<th>Carbon Tax (GBP per kWh)</th>
<th>Productivity (lnGBP)</th>
<th>Cloud Budget (GBP)</th>
<th>Hardware Budget (GBP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1Q</td>
<td>0.005</td>
<td>6.79</td>
<td>10000</td>
<td>12000</td>
</tr>
<tr>
<td>20Q</td>
<td>0.005</td>
<td>6.87</td>
<td>10000</td>
<td>11000</td>
</tr>
<tr>
<td>40Q</td>
<td>0.005</td>
<td>6.87</td>
<td>10000</td>
<td>10500</td>
</tr>
<tr>
<td>4Q</td>
<td>0.05</td>
<td>6.86</td>
<td>9000</td>
<td>11000</td>
</tr>
<tr>
<td>8Q</td>
<td>0.05</td>
<td>6.86</td>
<td>8000</td>
<td>10000</td>
</tr>
<tr>
<td>20Q</td>
<td>0.05</td>
<td>6.87</td>
<td>5800</td>
<td>8000</td>
</tr>
<tr>
<td>40Q</td>
<td>0.05</td>
<td>6.86</td>
<td>5100</td>
<td>9000</td>
</tr>
<tr>
<td>2Q</td>
<td>0.15</td>
<td>6.86</td>
<td>4000</td>
<td>8500</td>
</tr>
<tr>
<td>8Q</td>
<td>0.15</td>
<td>6.86</td>
<td>5000</td>
<td>9000</td>
</tr>
<tr>
<td>20Q</td>
<td>0.15</td>
<td>6.86</td>
<td>4600</td>
<td>9000</td>
</tr>
<tr>
<td>40Q</td>
<td>0.15</td>
<td>6.86</td>
<td>5000</td>
<td>8700</td>
</tr>
</tbody>
</table>

Results Table 5.7 provides a summary of results for the Set 2 Model B with SME agents and ICT provider agents. The results given for Production, “Cloud” Budget and Hardware Budget represent the centre mass of the SMEs represented on the scatter plots. The SMEs started with an average of GBP 330,000 at time step zero, a given 10 ICT provider agents and 3000 SME agents. The productivity is taken from the Hardware v Productivity plot and the Cloud Budget is the corresponding output for the given level of production.

The results of Set 2 Model B show that the overall spend of SMEs on ICT decreases as carbon tax increases in the scenario where there both SME and ICT provider agents.

5.5 Conclusion to Chapter 5

We can draw conclusions based on relative movement as parameters are changed. The system is in silico where it must be remembered that all parameters not included in the system are assumed to be held constant. In reality, there could be parameters unaccounted for, that would change with time, and affect the procurement behaviour of ICT managers. Therefore, all conclusions must be made with that caveat in mind. A good example would be that it was assumed that the SMEs would pay between 8p per kWh.
and 20p per kWh based upon typical energy prices in 2014-2015. However, it is possible that there could be a change in the emergent behaviour if there was a significant increase or decrease in the mean price of energy paid by SMEs.

When the experiments were run, the simulation would stop at the time step dictated at the beginning of the sequence. For example, if the simulation was set to run for four quarters, the experiment cycles through the algorithm four times and publishes the results at the end as a set of three scatter plots (“cloud” versus hardware spending, “cloud” budgets versus productivity and hardware budget versus productivity as shown in Figures 5.1, 5.2 and 5.3). The simulation was not biased or reversible. Every permutation of the simulation had to run sequentially. The emergent behaviour observed could be slightly different, however the aggregated effect of observing 10,000 SME agents should negate the worst effects of variances in starting positions of the SME agents when the experiment is reset. Each of the permutations were run at least 12 times to overview the repeatability of the model. The large number of SME agents per simulation run reduced the probability of outliers affecting the results.

The effects of “lock-in” and peer-pressure were modelled in the simulations by a segment of code that took a random number of SMEs and made them approach the aggregated mean values for “cloud” and hardware budgets. This thereby mimicked the effects of ICT managers influenced by a crowd of their peers.

In absolute terms the amounts forecast for cloud and hardware budgets by the model is comparable with the real-life data that are reported by the CBI and ONS. In 2014, the mean revenue for a UK based SME was GBP 330,000 and their expenditure on ICT hardware and services was GBP 16,000). A market survey by GE Capital of UK SME ICT expenditure in 2015 uncovered an average anticipated spend of GBP 30,000 for 2016. This figure is even closer to the total budget forecast by the Set 2 models. This is a strong indicator that the model reflects real life and addresses the second part of the research question; that the agent based models developed are useful in assessing how the ICT procurement behaviour can be influenced by carbon taxes.
Chapter 5 References:


Chapter 6: Conclusions and Future Work

6.1 Conclusions:

The results from the Set 1 and Set 2 models developed in this thesis allow us to draw the following conclusions:

- That agent based models are a suitable method of analysing environmental policies.
- That significantly higher levels of carbon tax would be required to have a significant effect on ICT procurement behaviour amongst UK SMEs.

Addressing the research questions posed in chapter 3.

The principle conclusion based upon the results of all the models is that the effect of carbon taxes on purchasing behaviour of SMEs can be modelled using agent based models. Another key conclusion is that the per unit electricity costs in the UK would have to be significantly greater in both proportional and absolute terms than they are at present to see a shift in the ICT purchasing behaviour of SMEs in the UK from hardware to “cloud” solutions. The Set 1 models (NetLogo) used a proportional approach and demonstrated a dramatic shift in hardware purchasing to “cloud” systems at a carbon tax above 200% of current values. The later Set 2 models written in Java demonstrated that the Climate Change Levy would need to be at least 5p per kWh of electricity to produce a notable change in the mid-point of SME agent cluster representing a greater proportion of ICT spending applied to “cloud” solutions, a 1000% increase over the 2015 CCL level. To see a significant movement in the positions the value was in the order of 15p per kWh of electricity.

Once we accept the premise that ICT can be treated as a form of capital for production in SMEs (Matteucci et al, 2005), then several conclusions can be drawn from the Set 1 and Set 2 model simulations conducted for this thesis. Primarily, that the use of simple agent-based models using Markov chains show great potential as a research technique for the procurement of ICT hardware and services. Their construction in Java as software objects allows for additional complexity to be added later and the freedom to insert real life data using many options. It is possible, for example, to add the
functionality to read MS-Excel files allowing the possibility to accept data (if it were forthcoming) directly from firms in the market place. Additionally, the use of agent based models are, indeed, useful in the research of effects of environmental policy on free markets.

It is unlikely that there would be political will by a UK government to increase the CCL to the levels required to achieve a shift in purchasing behaviour and it is also likely that SMEs would be highly vocal in their opposition. This, it could be argued, could help businesses to become more competitive as in the long term it is likely that fossil fuels are going to increase in real term prices as developing nations continue to increase their usage.

It is highly probable that carbon taxes and other policy measures discussed in Chapter 2 would encourage the economy to “transition” to a lower carbon economy. However, it is likely to be at least ten years before there is conclusive proof from time series data analysis as to the effectiveness of these policies or whether it is the pricing effect of fossil fuels increasing in price and encouraging SMEs and consumers to become more energy efficient. It also highlights the importance of predictive research, building models that can test the likely outcomes of policy before implementation.

Much of the academic value of this thesis project is in the novel use of ABM analysis of ICT procurement in changing carbon taxation levels. At the time of writing, to the best of the knowledge of the author, no one has published anything similar. There is merit in this uniqueness. It is also important to state another use of this work is to predict likely behaviour patterns in markets due to policy instruments. This could provide a vital tool decision makers to support their policy decisions. The use of an accepted analytical tool, the Slutsky equation, and being able to observe emergent behaviour over the progression of time gives extra credence to the results of the simulations in this thesis. 

The results of Set 2 simulations closely matched to real life data, providing evidence that as well as answering research question of this thesis, accurate results were achieved relevant to real life scenarios.
6.2 Future Work:

The next step is to increase the complexity and therefore the realism of the simulation. There is great value in adding a more intricate financial trading element to the simulation, for example by development of a “matching engine” as described by Hu and Watt (2014). This is a section of code that would prepare matches between the SME agents looking for “cloud” and ICT hardware bundles from ICT Provider agents. This is more advanced than the current use of a “profile” parameter in the Set 2 Model B to produce the likely hood of a transaction between the SME agents and the ICT provider agents and potentially would lead to a more realistic interpretation of the ICT market where both venders and consumers interact in a changing market place where carbon taxes have the potential to influence buying patterns.

6.2.1 Generation of Additional Results and Statistics

The method of observing results of the Set 2 models is currently laborious. Running the simulations taxes the resources of a desktop machine and require over twenty minutes per cycle and the adjustment of several of the variables in the code itself. In order to generate more statistically robust results this process would need to be further automated. By automating the calculations of the centre masses in the scatter plots, and repeating the simulations for each set of parameters at least thirty times to produce a mean value for the centre mass and corresponding standard deviations this would enable the process to become more robust and give results to a higher number of significant figures.

In future versions of Set 1 models it would be of interest to add numerical values to the x and y-axis and thereby make forecasting of market responses possible.

6.2.2 Changing Preferences

Currently much of the bounded rationality of the ABM is in the preferences of the SME agents between “cloud” and hardware solutions. There is scope for additional research into the effects of changing relative and absolute preferences for the different technologies. It could be that in the future firms develop a strong preference for “cloud” solutions versus hardware installations.
6.2.3 The Addition of Government Agents

In the models the influence of government is through the implementation of the carbon tax. In future versions of the models it would be interesting to develop a feedback into the system to allow the carbon tax to be varied to achieve present goals. This could be combined with a measure of GHG emissions or have a target based upon the relative uptake of “cloud” versus hardware. This would create new emergent behaviour and could result in a simulation that would calculate the desired carbon tax level to achieve desired results.

6.2.4 The Addition of Users within Client Enterprises

It could be of interest to ultimately model users within the SME agents as agents in their own right, with each agent having specific budgets and technical requirements. For example, some agents could require remote working, others might require high power workstations for CAD or data analysis.

6.2.5 Examination of Different Environmental Policy Options

Carbon taxes are not the only policy options available to policy makers wishing to encourage market agents to select low carbon options. The real-life influence of the CCL is very much married to the policy of offering Climate Change Agreements. It would be of interest to model the effects of multiple environmental policies, independently and simultaneously. Future work could adapt the Set 2 models to directly compare the effectiveness of different policy options. A primary example would be comparing the effectiveness of an emissions trading scheme versus a carbon tax. This could be of great academic interest where two key approaches can be compared and contrasted without having to wait for time series data to be made available.

6.2.6 Application of Nash Equilibria and Game Theory

It would be of great interest to observe the effects of changing the ABMs in the models so that they can apply cooperative and non-cooperative Game Theory. The application of Game Theory is common amongst researchers of artificial societies and is valuable in gaining insight into other possible emergent behaviours – especially that ICT providers, for example, must compete with one another over multiple time steps and this often alters the observed behaviour.
In future versions of the Set 2 Model B a Nash equilibrium for ICT providers in the system could be generated to calculate the pricing structure for the hardware products and “cloud” services in the simulations. There would be pricing game between the ICT producers that a Nash equilibrium could be used to solve and the results applied to the models. This could evolve into Set 2 model C.

6.2.7 Survey of SMEs in the UK

In future research a scientific survey of UK SMEs would improve the robustness of the conclusions. If the preferences of ICT managers were calculated directly from SMEs in the UK rather than inferred from information from industry experts or publications than there would be even greater confidence in the outputs of simulations run and hence the conclusions made.

6.2.8 Addition of a demand function for the output of SME agents

The Set 2 models could be made more realistic with the addition of a demand function to complete the theoretical model. In future work the market where SME agents and ICT Provider agents operate would have both a supply and demand side. Pricing of goods and services would become a key factor for the market to clear.

6.2.9 Use of Industry Data

Even though a key strength of agent based models is to infer emergent behaviour from relatively data poor scenarios, their effectiveness is greatly enhanced when real life data is applied, Unfortunately, HP were unable, due to commercial sensitivity concerns, to provide suitable sales data that could be used in the confines of the research models. Future research, through the use of a non-disclosure agreement or using data from another multinational tier 1 ICT provider could be made even more realistic, building on what has already been done with real life data from the ONS and other sources.

6.2.10 Adding Data Centre Managers

Data centre managers working within the ICT companies could influence the service packages available to end user clients; their operational performance would have a direct effect on the cost structure of the ICT company. They are likely to be directly affected by carbon/energy taxes and their comparative performance in responding to such policy changes could give the firm they work for a relative competitive edge when
compared to rival firms competing for business in the same market space. These would be added as a separate class of agent.

6.3 Summary of Conclusions

As discussed above the results from the Set 1 and Set 2 models developed in this thesis allow us to conclude:

- That agent based models are a suitable method of analysing environmental policies.
- That significantly higher levels of carbon tax would be required to have a significant effect on ICT procurement behaviour amongst UK SMEs.

This topical and novel approach to researching environmental policy offers a new tool for policy researchers and could be developed further in the future through the evolution of the models to include additional relevant parameters and more real life data.
Chapter 6 References:

Appendix

Pseudo Code describing the Set 2 Models

Below is a description of the section of Java code that runs the SME Agents and calculates Revenue and Expenditure – Uses an Adapted Cobb-Douglas production function, called from a separate object described earlier in the methodology, where ICT is a factor of production for SMEs

This section of the code imports the following libraries available through Eclipse:
java.util.ArrayList;
java.util.List;
java.util.Random;

//java.util.ArrayList allows the program to arrange the SME agents in method suitable for development of an ABM. The agents are created at the very beginning of the run and then all data is stored for use in the next time step. The SME agents progress through the simulation until the pre-set end point.

To begin the SME agents are created as a class and each cycle represents a quarter of a year:

```java
public class SMEAgent {
    public static List<SMEAgent> agents = new ArrayList<SMEAgent>();

    What follows is a list of parameters used and or generated by this section of code:
    public double ICTbudget=4000;
    //average annual ICT expenditure = 16000 (2014) This includes software licences, training, hardware, cloud, printing,other expenses holding everything constant apart from cloud, hardware
    private double cloudBudget; calculated later in the code
    private static final double affectionThreshold=0.3;
    //The probability of SMEs being affected by others
    public double hardwareBudget = 6560/4; // Average 6560/4
    private double priceOfCloud= 0.05;
    //Average price per hour for a virtualized server designed for SME usage
    private double priceOfHardware=0.086;
    //The average price of a mid-specification server divided by the number of working hours it is likely to be in service
    private double costOfRunningHardware;
    //price of hardware is average price of PC/hour over lifespan + electricity cost ()
```
private double quantityOfCloud=400;  
// based on the average number of working hours per SME per quarter
private double quantityOfHardware=400;  
// as above
private double trustInCloud;  // done in constructor
// based on the preferences of the decision maker in the SME
private double trustInHardware;  // done in constructor
// as above
private double labour = 400;  // average man hours 1600/4  
// per quarter
private double capital=300000;  // 78204.08163;
// approximate UK average SME value
private double investment;
// for possible use in future versions – currently held constant and not used in this
generation of simulations. However, ICT is a factor of production in this model and the
preceding purchases becomes an endowment for the next time step.
private double overheads;
// as above
private double revenue;
// done in constructor
private double exp=50;
public static double carbonTax=0.005;
// Use the GUI to insert different values for the carbon tax
private double MRS;  // done constructor, also do it steps
private double electricityPrice;  // done in constructor
private boolean affectedByPeers=false;
private double initRevenue;
// 0.0552 used for ICTBudget on average
public static double aveRevenue=330000;  // AVERAGE

public static double getAverevenue() {
    return aveRevenue;
    // Average starting revenue entered in GUI at the beginning of the program's run cycle.

    // productivity, budget, capital, trustincloud, trustinhardware
    public List<Double[]> timeline = new ArrayList<Double[]>();
    private String name;
    // private ICTProvider provider;
    public double getICTbudget() {
        return ICTbudget;
    }
}

public SMEAgent() {
    super();
    // randomize whether the SME is affected by peers
    if (new Random().nextDouble()<SMEAgent.affectionThreshold){
        this.affectedByPeers=false;
    }else{
this.affectedByPeers=true;
}
this.trustInHardware= 0.30 + 0.70*new Random().nextDouble();
//This was based on gathering opinions from industry professionals

this.electricityPrice= 0.08 + 0.12*new Random().nextDouble()+this.carbonTax;
//based on average prices paid by UK SMEs in GBP per kWh

this.costOfRunningHardware=this.electricityPrice*0.3+this.priceOfHardware;
//based on a 300W average PC

this.trustInCloud=0.85*new Random().nextDouble();
//Based on feedback from professionals that there is less trust in cloud solutions than integrated hardware solutions owned directly by the SME

this.MRS=this.trustInCloud/this.trustInHardware;//1+(2-1)*new Random().nextDouble();
//Using the principles of Cobb-Douglas preferences

this.cloudBudget=this.calcCloudBudget();
//this generates the cloud budget from the MRS and the hardware budget (itself calculate from preferences and a total ICT budget – the Total ICT budget is calculated using a production function where the endowment ICT provides the SME with a factor of production. The code that generates this value is discussed in

//The section below calculates the starting revenues for each of the individual SME agent – the average starting point is taken from the GUI.

double precision = new Random().nextDouble();
if(d<0.993){
    this.revenue=50000 + 660000*new Random().nextDouble();
    this.labour= 450 + 22050*new Random().nextDouble();
    this.hardwareBudget=2000 + 4000*new Random().nextDouble();
}
else if (d<0.997){
    this.revenue= 660000+ 1340000*new Random().nextDouble();
    this.hardwareBudget=60000 + 120000*new Random().nextDouble();
    this.labour= 450 + 22050*new Random().nextDouble();
}
else{
    this.revenue=1000000+ 1500000*new Random().nextDouble();

}//This represents the skewed market of SMEs in the UK – where the vast majority are small with around 10 to 20 employees and have a revenue around the GBP 330,000. However, there is a second tier of SMEs approximately 3% of the SME population that have a far higher revenue and more employees – they are significant consumers of ICT products and services and therefore have a disproportionate affect in the market.
}
// this.ICT budget = this.revenue * 0.05;
// set initial timestep 0
this.initRevenue = this.revenue;
double aff = -1;
if (this.affectedByPeers) {
    aff = 1;
}
this.timeline.add(new Double[]{this.cloudBudget, this.hardwareBudget, 0, 0, this.trustInCloud, this.trustInHardware, aff, this.labour});

// The ICT budget is a 5% proportion of the SME's total revenue.
// Here the code calling the production function, a separate section of code entirely, to calculate the revenue

// Below the code calculates the current time step Hardware budget – it includes the cost of electricity. It splits the SMEs into 2 groups based upon number of working hours provided by employees.

private void calcBudgets(int timeStep) {
    this.hardwareBudget = this.priceOfHardware * this.labour * this.revenue;
    if (this.affectedByPeers) {
        double aveHardware = 0;
        double aveCloud = 0;
        int similar = 0;
        for (SMEAgent a : SMEAgent.agents) {
            if (this.labour < 22050 && a.labour < 22050) {
                aveHardware += a.timeline.get(timeStep)[1];
                aveCloud += a.timeline.get(timeStep)[0];
                similar++;
            } else {
                aveHardware += a.timeline.get(timeStep)[1];
                aveCloud += a.timeline.get(timeStep)[0];
                similar++;
            }
        }
        aveHardware /= similar;
        aveCloud /= similar;
        if (this.cloudBudget < aveCloud) {
            this.cloudBudget += (aveCloud - this.cloudBudget) / 2;
        } else {
            this.cloudBudget -= (this.cloudBudget - aveCloud) / 2;
        }
    } else {
        this.cloudBudget = this.calcCloudBudget();
    }
}
```java
public void takeAStep(int timeStep){
    double productivity = AdaptedHempelEqn.SMEProductivity(this);
    this.revenue = productivity;
    //System.out.println(this.revenue);
}

private double calcCloudBudget(){
    // if (this.affectedByPeers){
        return this;
    // }
    //System.out.println(this.MRS*this.hardwareBudget);
    return this.MRS*this.hardwareBudget;
    // }
}

/**
private double calcHardwareBudget(){
    if (this.affectedByPeers){
        return 0;
    Else
    return (this.ICTbudget*this.trustInHardware);
}

public void lookAroundAndDecide(int timeStep) {
    // TODO Auto-generated method stub
    this.calcBudgets(timeStep);
    double aff=-1;
    if(this.affectedByPeers){
        aff=1;
    }
    this.timeline.add(new Double

Double precision
this.cloudBudget,this.hardwareBudget,this.revenue,this.trustInCloud,this.trustInHardware,aff,this.labour});

//here is where the code stores the data ready for the next time step until the preset end
where the results are published as a set of 3 scatter plots – Hardware Budget v Cloud Budget, Cloud v Productivity and Hardware v Productivity

End program
```
Pseudo Code for Production Function used in Set 2 Models

Below is the production function in pseudo code to calculate productivity of the SME agent with respect to capital (including ICT capital).

```java
public class AdaptedHempeEqn {
    //C is a constant drawn from derivation
    private final static double C = 7;
    //Gamma1 Hempel's experimental data
    private final static double gamma1 = 0.686;
    //Gamma2 Hempel's experimental data
    private final static double gamma2 = 0.189;
    private static int counter=0;

    public static double SMEProductivity (SMEAgent agent) {
        double ICTRestOfSpend = agent.getICTbudget() - agent.getHardwarebudget();
        //Takes into account that not all the ICT budget is spent on hardware or cloud services.

        /*System.out.println(agent.getHardwarebudget()+" +agent.getCloudBudget() + " +
                             +(gamma1 * ln(agent.getLabour())+" +gamma2 X ln(agent.getCapital()))
                             +" +agent.getInitRevenue());
        */

        if(agent.getHardwareBudget()+agent.getCloudBudget()>agent.getInitRevenue()){
            counter++;
        }

        System.out.
        println( (ln(C) +agent.getExp() X ln(agent.getCloudBudget()+agent.getHardwarebudget()) +
                        agent.getExp() X (Math.log(agent.getCloudBudget()+agent.getHardwarebudget()) +
                        (gamma1 X ln(agent.getLabour())+gamma2 X ln(agent.getCapital()))))
        );
        //here the code runs the production function ready for the SME agents to use the outputs

        return ln( (ln(C) +agent.getExp() X ln(agent.getCloudBudget()+agent.getHardwarebudget())
                        + agent.getExp() X ln(agent.getCloudBudget()+agent.getHardwarebudget())
                        +(gamma1 X ln(agent.getLabour())+gamma2 X ln(agent.getCapital()))));
        end loop
```

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Sample Scatter Plots produced by Set 2 Model Simulations:

Cloud v Hardware Budgets, average SME starting revenue GBP 330000, 4 quarters and 0.005 GBP per kWh CCL

Cloud Budget v lnProductivity, average SME starting revenue GBP 330000, 4 quarters and 0.005 GBP per kWh CCL
Hardware Budget v ln(Productivity) average SME starting revenue GBP 330000, 4 quarters and 0.005 GBP per kWh CCL

Cloud v Hardware Budgets, average SME starting revenue GBP 330000, 40 quarters and 0.05 GBP per kWh CCL
Cloud Budget vs ln Productivity, average SME starting revenue GBP 330000, 40 quarters and 0.05 GBP per kWh CCL

Hardware Budget vs ln Productivity, average SME starting revenue GBP 330000, 40 quarters and 0.05 GBP per kWh CCL