BoR (19) 246

Study on the determinants of investment in VHCN – a System Dynamics approach:

Volume 2: Literature Review

November 2019

Disclaimer:

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1 Introduction

1.1 Purpose of this Review

The relationship between regulation, competition and investment in broadband infrastructure and technology has been widely discussed in academic literature and in papers prepared by regulators and consultants, from both theoretical and empirical perspectives. There have also been a number of reviews of that literature that identify the various strands of thinking and analysis regarding the relationship between regulation and investment (Cambini and Jiang 2009, Briglauer, Frübing and Vogelsang 2014, Krämer and Schnurr 2014, Abrardi and Cambini 2019).

This review of relevant literature has been prepared as part of a research project for the Body of European Regulators of Electronic Communications (BEREC) into the determinants of investment in Very High Capacity Networks (VHCN) using a Systems Dynamics approach.

The term "Very High Capacity Networks" has been introduced in the new European Electronic Communications Code (the Code), where it is defined as[1]:

> *"…an electronic communications network which consists wholly of optical fibre elements at least up to the distribution point at the serving location, or an electronic communications network which is capable of delivering, under usual peak-time conditions, similar network performance in terms of available downlink and uplink bandwidth, resilience, error-related parameters, and latency and its variation" (Article 2 (2))*

The Code places an obligation on National Regulatory Authorities (NRAs) to promote access to, and take up of, VHCNs by all citizens and businesses in the EU[2], which the EU sees as being in the interests of its citizens[3]. However, as the extent of end-user access to such networks varies across Member States, it is necessary for NRAs to understand what determines the level of such investment so that appropriate measures can be put in place to increase availability.

System Dynamics is a well-structured and proven methodology to study dynamic complexity, both qualitatively and quantitatively, and so captures how various factors might influence outcomes: in this case investment in VHCNs. The system in which VHCN investment takes

[1] DIRECTIVE (EU) 2018/1972 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 establishing the European Electronic Communications Code
[2] ibid. Art 2(a)
[3] ibid. Art 2(d)

place is complex, comprising regulators, network operators, investors, retailers and, of course, business and residential consumers, each adopting behaviours and/or strategies in response to the other. Complexity arises because this market system is:

- Dynamic – change occurs over different timescales. Infrastructure investments may require long pay back periods, sometimes longer than investors want to recognise.
- Tightly coupled – regulators and providers interact strongly with one another.
- Governed by feedback – actions feedback on themselves. This is observed, for example, in investment cycles, when the return from early investment provides the confidence to invest further.
- Non-linear – need to explicitly recognise non-linear responses between cause and effect.
- Counterintuitive – cause and effect may be distant in time and space and can demonstrate that policies can cause very different behaviours over the short and long term.

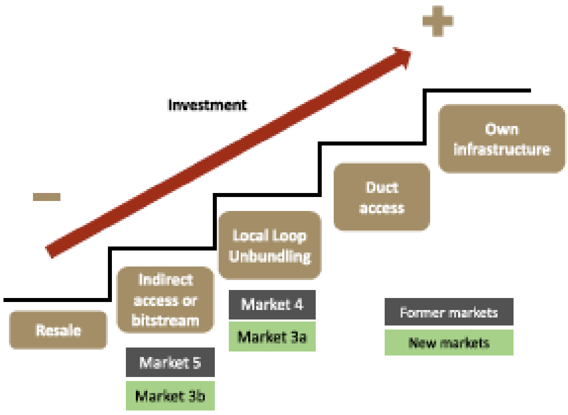
The Code was only formally approved by the European Union in December 2018 and thus the term VHCN has not been adopted in any of the various papers reviewed here. The reviewed papers tend to refer to Next Generation Access Networks (variously NGN, NGAN or NGA, herewith NGA unless included in a quote from a paper that uses a different acronym) where NGA tends to mean a network using fibre optics at least as far as the street cabinet but including fibre to the home. NGA also includes other technologies, such as DOCSIS 3.x on cable, capable of delivering higher access speeds than the legacy copper network. In reviewing the literature, therefore, it is not possible to examine the determinants of investment in VHCN specifically, but it is possible to learn about determinants of, and deterrents to, investment in a new generation of high speed networks. Where an NGA is fibre to the home (FTTH), rather than fibre to the cabinet (FTTC), there may be no real difference between NGA and VHCN.

Whatever the precise definition, intuitively it would seem reasonable that similar determinants would affect investments in VHCN and in NGA. However, we should note that there may be different conditions that have not yet been researched in the literature.

1.2 Methodological Approach to the Literature

A well-known approach to encouraging investment in telecommunications networks is the "ladder of investment", a term first coined by Prof. Martin Cave (Cave 2004), illustrated in Figure 1 below.

Figure 1: The Ladder of Investment



(Frias and Martinez 2019)

In a later paper (Cave 2006), Cave describes the rungs on the ladder from retail at the bottom to an unbundled copper loops at the top. The idea behind the ladder of investment was that entrants could build a market presence using a low cost entry mechanism (bitstream) and progress up the ladder as they became more established. Lower rungs of the ladder could be removed as competition is established further up it. Regulated prices would send the correct build or buy signals so that competitors could make efficient investments. The approach was embraced in the 2002 EU common regulatory framework.

A retrospective paper on the concept (Cave 2014) refers to the ladder stopping at unbundled local loops as a "short version". He suggests that the ladder concept could be said to have failed if competitors had not invested in their own independent infrastructure. Cave, however, does not see this as a failure as it would be unrealistic to expect there are no limits to infrastructure replicability. Further, companies have invested in developing their own fibre networks that have not previously used LLU; for example CityFibre in the UK and Masmovil in Spain.

Arguably, the Code places a greater emphasis on investment in alternative fibre infrastructures than its predecessor, the Common Regulatory Framework (CRF), adopted by the European Union in 2002. The "Framework Directive" 2002[4] required National Regulatory Authorities (NRAs) to safeguard competition and promote infrastructure competition "where appropriate" and to promote "efficient investment" (Art. 8.5(c) and (d)). Under the CRF, much of the regulation imposed by NRAs focussed on that short version of the ladder of investment, though not exclusively so, through effective regulation of access to incumbents' infrastructure.

[4] DIRECTIVE 2002/21/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 7 March 2002 on a common regulatory framework for electronic communications networks and services (Framework Directive)

The Code builds on the CRF and is more explicit about promoting investment in VHCN, stating in Recital 3:

> *"In its communication (…) setting out a Digital Single Market Strategy for Europe, the Commission stated that its review of the telecommunications framework would focus on measures that aim to provide incentives for investment in high-speed broadband networks."*[5]

Whilst it may be more an evolution than a revolution, the Code seems to place more emphasis on a longer rather than a shorter interpretation of the ladder of investment and towards developing a competitive infrastructure market rather than effective access to existing infrastructure. This is a matter of emphasis, as the CRF also required NRAs to encourage efficient investment in infrastructure.

In this review of the literature, we examine what previous authors have said about the conditions needed to make the leap from the short version of the ladder of investment to one that includes VHCN, although not necessarily couched in the language of the ladder of investment. However, whereas the ladder of investment theory focussed on incentives for non-incumbent operators to invest, our review includes both entrants and incumbents.

To consider the determinants of investment in any project, we must first consider why a firm invests. At its most simple, a firm or investor will invest in a project if the expected cash flows from that project exceed the expected costs, including the cost of capital, over a given period and when compared with the next best use of the capital.

The simplest determinant of investment in VHCN is, therefore, whether an investment in a particular VHCN project will earn a higher profit than the next most profitable use of investment funds over a period of time. The alternative project may be in the same technology in a different location, e.g. a different country, or in a different technology that is expected to make higher returns. What investors want to establish is whether the expected cashflows from an investment will exceed the expected costs, including a discount rate that represents the cost of capital. This is captured in the well-known Net Present Value (NPV) equation shown below:

$$NPV = -K + \Sigma_{t=1}^{T} \frac{\pi_t}{(1+r)^t}$$

[5] More specific references can be found in Arts 61.1, 73.2(e) & (f) and 74.1.

The investment capital (K) is made a time *t=0* and generates a cash flow at each future period of time (π_t) which has a present value[6] at period 1 of $\pi_1/1+r$, where *r* is the threshold, or hurdle, rate of return required by the investor.

Dobbs (2000) defines a decision rule as to whether to make an investment based on the NPV:

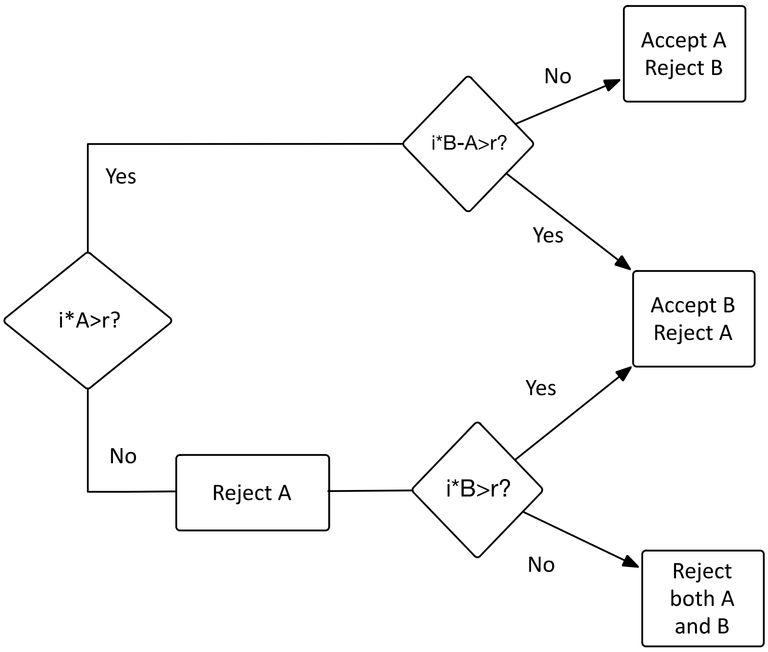
Accept the project if NPV > 0
Reject if NPV < 0
Indifferent if NPV = 0.

Charles Rivers Associates (2012) explains succinctly:

> *"Investment will take place when [potential investors] believe that the NPV is high enough; not when regulators deem it so"* (p. 38)

As noted above, however, an investor will make a decision about whether to invest in a project against the next best use of capital, i.e. an alternative project. This decision is presented as a simple decision tree in Figure 2 below where the investor is choosing between projects A and B (Dobbs 2000).

Figure 2: Choosing between projects using the incremental IRR



[6] The discounted value of a financial sum arising at some future period.

As the choice of investment is between two projects, and assuming both have a positive NPV, Dobbs' decision rule above can be amended to:

Accept Project A if $NPV_A > NPV_B > 0$
Accept Project B if $NPV_B > NPV_A > 0$
Indifferent if $NPV_A = NPV_B > 0$

Regulation and public policy can affect the variables in the NPV calculation in one or more of three ways:

- They can raise or lower the capital investment required by actions that raise or lower the economic barriers to entry. For example, it can allow or disallow access to existing physical infrastructure, where such infrastructure is available;
- They can raise or lower expected cash flows, for example by implementing measures that aggregate demand, reduce prices or impact operating costs; and/or
- They can raise or lower the hurdle rate, for example by providing or not providing regulatory certainty that decreases or increases the investor's level of risk, affecting the cost of capital.

1.3 Structure of the Review

Before reviewing the literature on investment in NGNs, we first provide some more detail on the System Dynamics methodology, providing a brief review of its development and how the technique has been used in policy discussions (Section 2). More detailed information on the methodology is presented in Annex A.

The main body of the literature review (Section 3 - 5) takes the NPV model and examines what various researchers have said about the effect of regulation on:

- Capital investment
- Demand (a proxy for incoming cash flows)[7] and,
- The cost of capital, including regulatory risk.

We first examine what we can learn from the literature about regulatory actions that increase or lower the capital required to make investment in fibre networks, for the incumbent operator and the entrant. This will cover both the direct costs of network development and, what has been termed, the opportunity cost of building a separate network that bypasses an existing network to which the investor may gain access at regulated or unregulated price (Bourreau, Cambini & Doğan 2012).

[7] Little has been said in the literature about reduced operating costs. However, it is generally accepted across the industry that fibre optic networks have lower operating costs than copper networks.

Secondly we will examine what the literature tells us about general economic conditions, direct actions (for example subsidies) and the effect of competition on demand.

Thirdly, we review literature on regulatory risk and how it affects firms' cost of capital, or hurdle rate in the NPV equation. However, it should also be noted that a decision to invest in a network may not be a "now or never" choice and that an investor may choose to delay an investment or make investments in stages. This provides the investor with a "Real Option" on the timing of the investment. The possible effect of Real Options on investment choices, and how regulators can respond to these choices will also be discussed in this Section of the review.

1.4 About this Review

Causal Loop Diagrams

Throughout the review we will represent findings from the articles in the format of Causal Loop Diagrams (CLDs), which perform an important role in System Dynamics models. A brief introduction to the notation used in the diagram is shown below. These diagrams show logical links between different concepts where one concept impacts another through a causal link. A more detailed introduction to the principles of System Dynamics and further information on diagramming approaches are shown in Annex A.

With each CLD we will provide a brief explanation of what it represents to assist readers. It should be noted that these CLDs are this review's authors' representation of the findings and not those of the original researchers. The CLDs may add extra steps to complete or explain the logic of the argument that may have been implied but not necessarily stated in the original research. The CLDs also do not attempt to critique or comment on the findings of the original papers.

The CLDs use links between the concepts to denote that there is a causal relationship from the concept at the tail of the link to the concept at the head of that link. The colour of the arrow denotes the nature of the relationship where **green** indicates that it causes a change in the same direction and **red** indicates that it causes a change in the opposite direction.

A simple example of these causal arrows is shown in Figure 3 where there are three concepts of "Costs", "Revenue" and "Profit". An increase in Revenue will make Profit go up (all other things being equal), which is a change in the same direction hence a green link. Similarly, if Revenue goes down then Profit will go down, still a change in the same direction so the green link correctly represents this. If Costs go up then Profit will be reduced, which is a change in the opposite direction so a red link is used. Similarly the red link correctly represents that a fall in Costs will lead to an increase in Profit.

Figure 3: Example of causal linked concepts of costs, revenue and profit

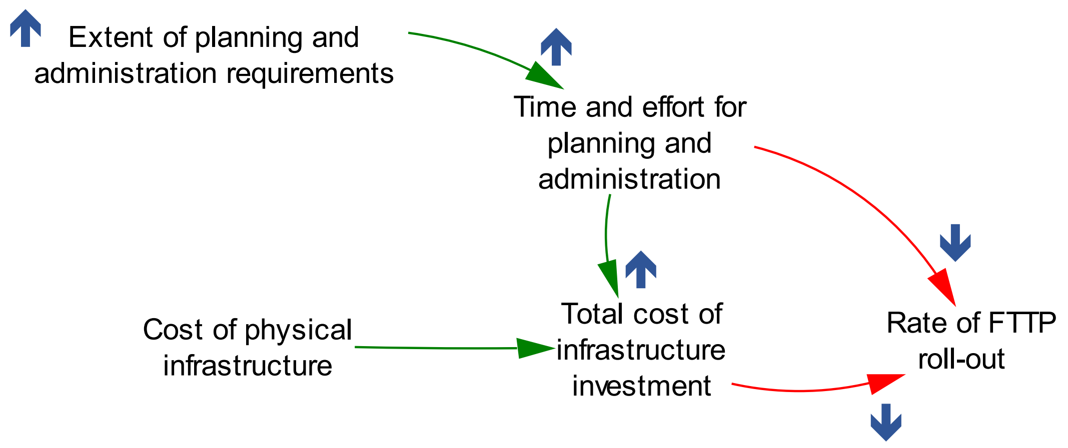
Up and down arrows help to illustrate the causal relationships described or tested in the literature. An up-arrow indicates either that the factor is typically increasing, or that the research is examining the consequences of a high value or increase in that factor. Down-arrows indicate that the factor is typically declining or that the consequences of a low value or decline is being tested by the research. Typically an up or down arrow will be placed by the concept(s) specifically mentioned by the paper. Up and down arrows will then be placed on the causal links that propagate the impact of the concept(s). If there are no up or down arrows shown for a concept or arrow then it should be assumed that the concept remains constant for the purposes of the discussion.

For example, in Figure 4, there is a positive (green) causal link between “Extent of planning and administration requirements” and “Time and effort for planning and administration”, so if the former is high then the latter will be high, hence both are shown with up arrows. There is a negative (red) causal link between “Time and effort for planning and administration” and “Rate of FTTP roll-out”, since if the former is high it will increase the time required to obtain planning permissions and any other necessary administration, which can be seen by the down arrow on the link into the “Rate of FTTP roll-out”.

The impacts of causal arrows can be combined. A high “Time and effort for planning and administration” will tend to add higher capital costs, shown as a green link to “Total cost of infrastructure investment” which has a red link to the “Rate of FTTP roll-out” since it damages the financial business case.

Note that it is acceptable for “Time and effort for planning and administration” to influence “Rate of FTTP roll-out” twice. One impact is through time and capacity constraints, the other impact is financial, through increased capital costs of infrastructure deployment. Finally, we assume in this example that the “Cost of physical infrastructure” stays constant so there are no up or down arrows for this.

Figure 4: Illustrating the directions of change of causally related factors



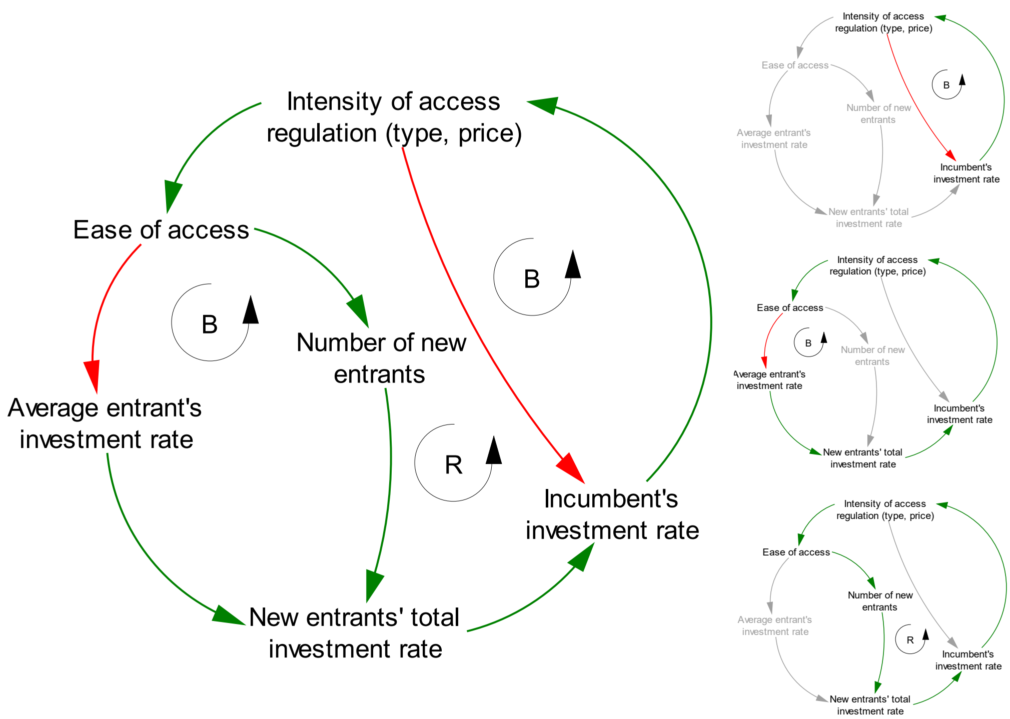
The relationship between the causal link colours and the up/down arrows is that a green link will keep the up/down arrows pointing in the same direction while a red link arrow will reverse the direction of the up/down arrow.

In Figure 4, the causal relationships run from the two 'independent' variables on the left to the 'dependent' variable to the right. There is no feedback, so this is strictly just a 'causal diagram'.

Figure 5 shows a diagram with causal loops, which are shown to the right of the diagram. This is where a set of causal arrows create a closed loop. The example shows three causal loops. These loops can be (B)alancing where they tend to push values to an equilibrium state, or (R)einforcing where a change can cause an accelerating relationship either upwards or downward depending on the nature of a change. The type of loop is identified by counting the number of red links in the loop. If there is an odd number of red links then it will be a balancing loop. If there are no red links, or there is an even number of red links, then it will be a reinforcing loop. The presence of loops is highlighted by the B and R symbols within a circular arrow showing the direction of the loop. It may not always be obvious which links are part of which loop, in which case insert diagrams will be used to highlight each loop. Any genuine feedback loops that do feature in the literature will be explained at the relevant point in the text.

Note that in Figure 5 the "Incumbent's investment rate" is subject to both up and down influences. A **?** symbol is used on the causal link into "Intensity of access regulation (type, price)" because the direction of change depends on which of the two impacts on "Incumbent's investment rate" is greater.

Figure 5: Illustrating a causal loop diagram with feedback loops (loops highlighted on right)



Network Nomenclature

Through the review the term ‘**physical assets’** refers to civil engineering assets of network operators, such as ducts and poles. The term ‘**network infrastructure’** refers to the cables (including copper, fibre and hybrid fibre coax (HFC)) that transports communications signals.

Operator Types

Three types of operator are generally referred to in the review:

‘(Former) incumbent’: The former monopoly provider of telecommunications services.
‘(New) entrant’: A firm that has entered the market since the liberalisation of the telecoms markets. Such a firm might be a reseller or a builder of an alternative network.
‘Cable company’: A firm offering broadband access via Hybrid Fibre Coax (HFC) cables. These firms may have originally been TV distributors but now also provide broadband access.

‘Efficient Investment’

Article 3.4(d) of the Code places an obligation on NRAs to promote “efficient investment”. The term “efficient investment” is not defined but can be taken to mean that, for example, network duplication should not take place in an area that can only support a single network.

The literature tends to use capital expenditure (capex) by the investing company as the variable used for investment and does not assess whether the investment is efficient or not.

2 Capital Investment

In this section, we consider regulatory interventions that affect both the direct and indirect costs of building an NGA network and therefore the amount of capital needed by the investor. Where appropriate we consider these effects separately for the incumbent operator and the entrant.

2.1 Direct Costs of Infrastructure Deployment

2.1.1 Access to Physical Infrastructure

Building a new fixed telecoms network is a civil engineering project. An investor needs to dig trenches to lay cables, often in a duct of some description. In some areas it may need to erect poles from which to hang cables. Estimates vary about the proportion of the cost of network build accounted for by civil infrastructure, but a commonly used estimate is around 60% - 80% (FTTH Council Europe 2014, DCMS 2016). Of course, electronic communications networks already exist, as do other utilities, and this existing physical infrastructure may be reusable to reduce the civil engineering costs.

The potential for access to existing physical infrastructure to reduce the cost of investment has been recognised by the European Union. In 2014, the Council and Parliament approved the Broadband Cost Reduction Directive (BCRD)[8] that sets out the obligation on Member States to ensure telecoms operators can access the physical infrastructure of a variety of utility networks for the purpose of building broadband networks. In addition, Art. 72 of the Code empowers NRAs to place an obligation on an undertaking with Significant Market Power (SMP)[9] to provide access to its existing ducts and poles. In theory, at least, access to telecoms and other utilities' physical infrastructure should be equally effective at reducing investment costs in civil engineering.

The importance of physical infrastructure access, in particular ducts, to the roll-out of FTTP is noted in BEREC (2016), which considers that the availability, or lack thereof, of high-quality ducts is a key determinant in the type of NGA (FTTP or FTTC[10]) rolled out in EU Member States:

> *Where a duct network of the incumbent operator is available, cost oriented access to these ducts has proven a very efficient means to allow alternative operators – in*

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[8] DIRECTIVE 2014/61/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 15 May 2014 on measures to reduce the cost of deploying high-speed electronic communications networks

[9] A concept equivalent to dominance in competition law. Under EU electronic communications regulations National Regulatory Authorities (NRAs) are required to review certain markets to establish if any firm enjoys a position of SMP and, if so found, impose regulatory obligations that support competition in the relevant market.

[10] Fibre to the Premises, Fibre to the Cabinet.

> *addition to the incumbent – to rollout fibre-based networks to the customer. Countries like [Spain, Portugal and Lithuania] have a relatively high FTTP coverage and at the same time significant rollout of FTTP of alternative operators. In [France], although the coverage is not yet as significant, there is a high share of FTTP rollout from alternative operators.* (p35)

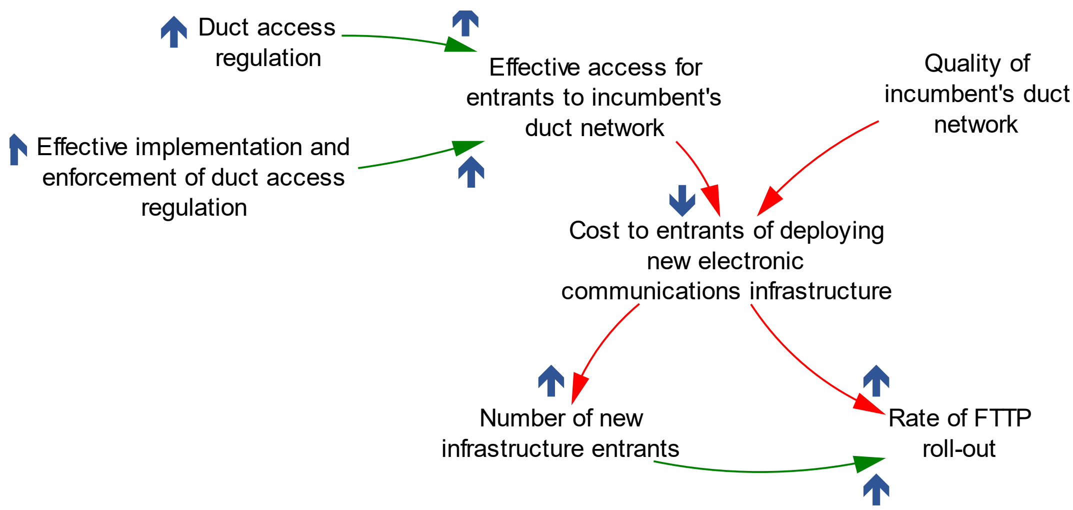
BEREC goes on to say that "*access to ducts lowered the costs of deployment and led to significant FTTP roll out of alternative operators*" (p35).

A report prepared by WIK Consult for Vodafone (WIK Consult 2017) benchmarks physical infrastructure access (PIA), in five EU Member States: UK, France, Germany, Portugal and Spain. It finds that France, Portugal and Spain have the most advanced operational conditions for PIA, and at the time their report was prepared, were the only ones to report the level of take-up. These three countries all have legislation on this issue that predates the BCRD.

The WIK report also finds that the regulations governing physical infrastructure access (PIA) are very important to its success. Poor regulation leads to poor uptake of PIA as it does not reduce the cost of network deployment as much as could be the case. This is an important finding, as it is not just the availability of ducts that matters, but the effectiveness of access regulations, including price. The regulator can do little to affect how much duct is physically available but can ensure effective regulations that govern access.

The findings of these two articles have been represented as a CLD in Figure 6. The CLD shows that regulated access to the incumbent's duct network along with effective enforcement of that regulation will create effective access to the duct network and reduce infrastructure costs. The degree of cost reduction depends on the quality of the duct network, with no benefit to be gained if cables are directly buried. Cost reduction for infrastructure will increase the number of infrastructure entrants and increase the speed of roll-out.

Figure 6: How access to incumbent's duct network supports FTTP roll-out



The European Commission reviewed the effectiveness of the implementation of the BCRD in 2018 and found only limited take up in six Member States – Germany, Ireland, Spain, France, Italy and Portugal – although it also found emerging interest in Austria, Belgium and Sweden (European Commission 2018, p. 7-8). BEREC (2019) has found a number of limitations to the BCRD's ability to act as a safety net, describing the BCRD as "not very prescriptive on potential approaches with regard to access to physical infrastructure". BEREC finds in particular that the BCRD is not designed to deal with problems arising from vertical integration[11].

Frontier Economics (2018) provides a number of examples of infrastructure assets from other sectors being used to deploy fibre on a commercial basis that suggests some broader interest than found by the European Commission. These examples include:

- German regional Fibre To The Premises (FTTP) operators belonging to local utilities using passive infrastructure after market liberalisation in 1998[12];
- The Spanish operator Adamo working with a local electricity company to cover 100% of the Cantabria province with FTTP;
- SIRO, the joint venture between Vodafone and the Irish electricity company ESB, deploying FTTP using ESB's electricity distribution network infrastructure;
- Enel, Italy's major power utility, that plan to roll-out fibre using its electricity network to 9.5 million premises;

[11] See BEREC (2019) Annex 4, p. 37.
[12] Coverage by such networks is limited.

- The UK operator SSE that has announced a partnership with Thames Water to enable the distribution of SSE Enterprises Telecoms' fibre cables though Thames Water's waste water network;
- The use of the French electricity company's physical distribution network to support the deployment of fibre using its low and medium voltage poles; and
- Two New Zealand electricity companies (Northpower and Waikato Networks) being awarded concessions to deploy fibre as part of the government's national broadband plan.

BEREC (2019) considers the potential effect of defining a separate market for physical infrastructure if other utilities are found to be part of that market. If all physical infrastructure, including for example gas and water pipelines, are found to be in the same relevant market as telecoms ducts, this may result in the former incumbent operator not having SMP in that market and so only subject to regulation under the BCRD. In theory, whether access to physical infrastructure is under SMP regulation or the BCRD, it should lower the cost of investment in new networks.

The possible economic effect of duct access or sharing on the estimated costs of building fibre networks across the EU has been calculated by Domingo and Oliver (2011). They estimated that duct access will reduce the total cost of building alternative networks of €250 - €300 billion by around 50% to €160 billion. Feeding such a cost reduction into an NPV calculation would clearly have a significant effect on the outcome and so providing non-incumbent operators with access to existing ducts is likely to be a significant determinant of investment in VHCN, with WIK's caveat that regulations must be effective.

However, there is some scepticism as to the extent to which other utilities' physical infrastructure is a substitute for telecoms physical infrastructure. Ofcom finds that the infrastructure of other utilities is not an effective substitute giving eight reasons, including: lack of coverage, lack of access points and restrictive rules (Ofcom 2018a, pp17 - 19). This means that other utilities' physical infrastructure is not in the same relevant market as telecoms physical infrastructure.

Similarly, Arcep reviews the practicality of using sewerage and other utility networks for laying fibre-optic cables and concludes that the use of some of the infrastructures under analysis (i.e. underground networks for electricity, gas, water and heating) are not substitutes for physical infrastructure designed for telecommunications services (Arcep 2017 pp 34-35).

Vogelsang (2019) provides a word of caution. He suggests that possible symmetric regulation on physical infrastructure under Articles 59, 70 and 71 of the Code could harm investment incentives if it results in a reduced barrier to regulatory intervention. He accepts that sharing can provide strong cost reducing effects but suggests that if the sharing requirement is burdensome (which he does not explain further, but presumably means cost raising), this may dampen incentives for entrants to build new infrastructure, presumably by reducing potential returns. He suggests that the Code is lacking incentives for first movers.

However, the literature to date is only descriptive and there are not enough data yet available to conduct any empirical econometric analysis of the effect of physical infrastructure access on fibre deployment. Similarly, there is insufficient experience to determine whether a regulatory requirement to provide duct access may reduce incentives to replace ducts.

2.1.2 Administration Overhead Costs

Whilst physical infrastructure accounts for around 60% - 80% of network build, planning and administration account for a further 15% of the cost[13]. Analysys Mason (2017) identifies some of the elements of this cost as complying with:

- Noticing and permit schemes
- Road traffic management
- Planning permission

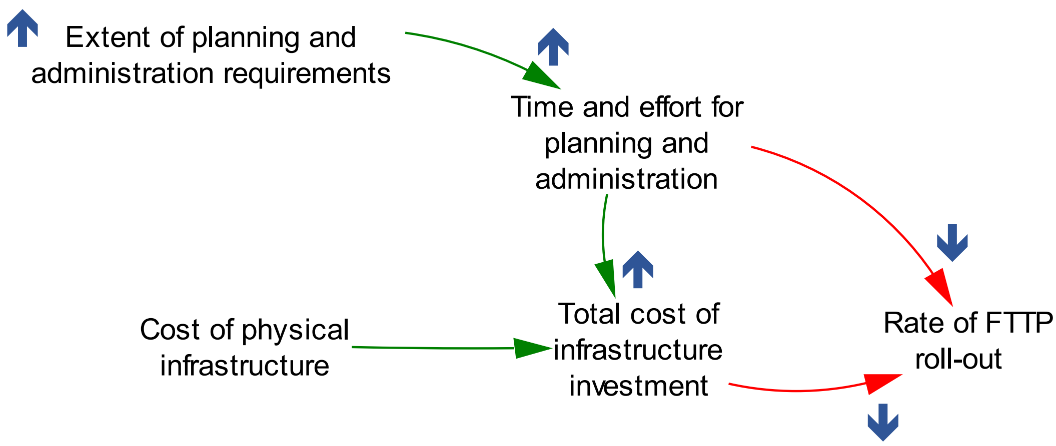
Local property taxes may also be added to this list if they applied to fibre networks.

Analysys Mason (2017) does not estimate the likely financial impact of these barriers. However, it is probable that the magnitude of any impact would be substantially less than physical infrastructure access, where it is available. What is also not discussed is whether such regulations may delay the timing of any investment and thus whether areas with less onerous regulations may see earlier investment. More costly regulations affecting construction may increase the option value (discussed below in Section 4.3) of delaying investment until demand and supply conditions become better known.

Figure 7 below illustrates the impact of planning and administration requirements for building FTTP (assuming that existing ducts cannot be used). A high planning and administration burden would increase the time and effort required for planning and administration. This will increase the total infrastructure costs which could decrease the rate of FTTP rollout, and could potentially act as a staff capacity bottleneck on the rate of roll-out. Note that the capital cost impacts could be relatively minor in comparison with the physical cost of infrastructure.

[13] Information supplied by a network operator.

Figure 7: Effect of Planning Costs on FTTP Roll-out



2.1.3 Spillover Effects

Some authors (Bourreau, Cambini, Doğan (BCD) 2012, Bourreau, Cambini and Hoernig 2012) have found the existence of spillover effects that benefit entrants if an incumbent already has invested in NGA. Spillover effects occur when an entrant's costs are reduced if the incumbent has already upgraded their network due to some second mover advantage, although it appears that BCD assume that the incumbent builds new physical infrastructure rather than reusing existing ducts and poles.

BCD explain what such spillover effects might be:

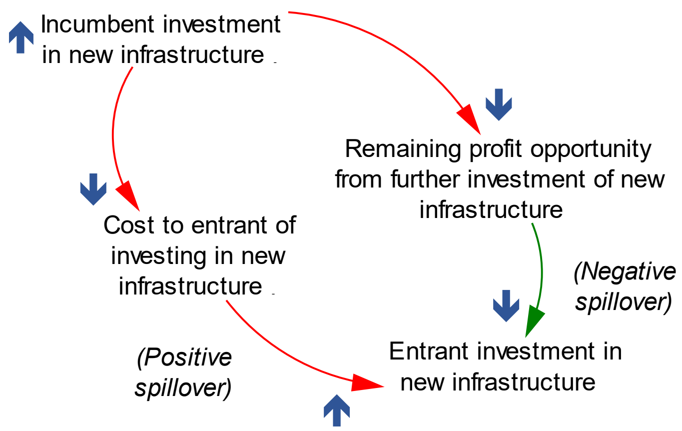
> *"… when the incumbent builds an NGA in a given zone, it may have to obtain administrative authorizations, to gather information on existing civil works or rights of way, etc., which generates some administrative and contractual costs. When the entrant decides to roll-out its own NGA in the same area, its investment costs can be lower if it can benefit from the incumbent's earlier efforts. One could also consider informational spillovers, as well as direct cost savings due to infrastructure sharing." (BCD (2012), Footnote 11)*

Where these spillover effects exist, therefore, the direct costs of network build by entrants are reduced, although the magnitude of any cost reductions is unknown. Whilst the literature seems to consider that such spillover effects only benefit the entrant, there is no reason why they shouldn't also benefit the incumbent if the entrant builds first, though probably to a smaller extent. Also not mentioned in the literature is the possibility of a marketing spillover effect, where the second mover gains from the marketing activities of the first network builder.

Not mentioned in the literature but counteracting these positive spillover benefits is the simple case of first mover advantage, i.e. the first firm to build a network in a given area gains a timing advantage, which cannot be matched by later entrants. Thus spillover effects may be positive, if they reduce the costs of later entrants, or negative if they raise the entry barriers for a second mover.

We have sought to capture these effects in the CLD in Figure 8 below. At the top, the incumbent makes an investment in a new infrastructure network. This has a **positive spillover effect** on the left hand-side if it **reduces the cost to the entrant** of building new infrastructure. The right hand side shows a **negative spillover effect** if the remaining **profit opportunity for the entrant is reduced** by the incumbent moving first. This, of course, has a negative effect on new infrastructure investment by entrants. The net effect on entrant investment in new infrastructure depends on the relative strength of the two forces.

Figure 8: Positive and Negative Spillover Effects



2.2 Indirect Costs

Perhaps the most discussed cost in the economic literature is the indirect, or opportunity cost. For the entrant, this arises from the difference between the cost of building its own network and the cost of wholesale access to the incumbent's existing network. For the incumbent, these are the difference between the profits it earns from providing other operators with wholesale access to its existing network and the future profits from an upgraded network, either from an expanded wholesale market or increased margin on access prices.

2.2.1 Entrants' Indirect Costs

An entrant making a decision to invest in VHCN faces a number of indirect costs that are not incurred by the incumbent.

Suppose that the entrant is trying to decide whether to invest in its own VHCN (Project A) against the alternative of continuing to use wholesale access from the incumbent (Project B). It needs to know whether the incremental profits from A are large enough to create a positive NPV in their own right and replace any lost profits from ceasing to provide services based on wholesale call. Following Dobbs' (2000) simple rule above, the entrant would face the decision rule shown below:

If $NPV_{VHCN} - L\pi_w > 0$ invest in VHCN
If $NPV_{VHCN} - L\pi_w < 0$ do not invest in VHCN
If $NPV_{VHCN} - L\pi_w = 0$ indifferent

This shows that for an entrant to invest in VHCN, its NPV from VHCN (NPV_{VHCN}) less any lost profits ($L\pi_w$) from its service based on wholesale access to the incumbent's legacy network, must be greater than zero for it to invest. The literature refers to this lost profit from wholesale access based products as an opportunity cost (Bourreau, Cambini, Doğan (BCD) 2012).

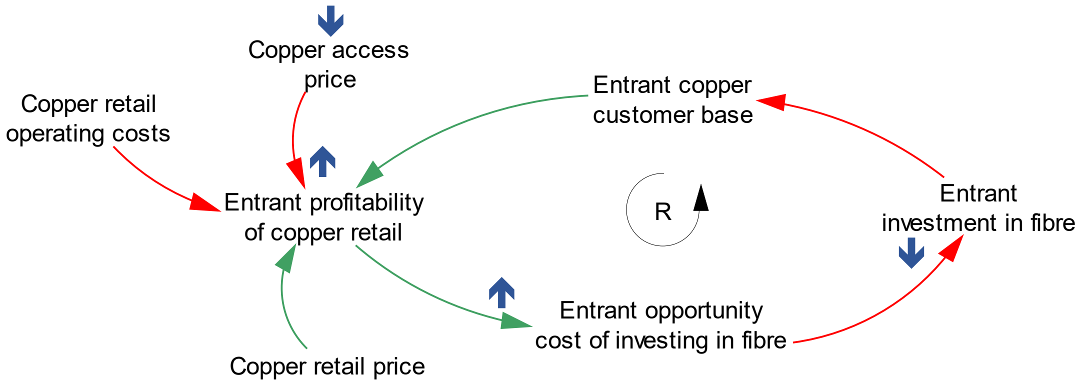
BCD develop a model in which access to an existing "old technology" network is available everywhere within a country and the incumbent and entrant compete in the retail broadband market. They then analyse both firms' incentives to invest in new technology as a function of the access price to the existing network. Their model highlights a "replacement effect" that reduces entrants' incentives to invest in a new technology when the access fee to the existing infrastructure is low. The replacement effect implies that, *certeris paribus*, a monopoly firm has lower incentives to invest in drastic innovations than a competitive firm, as it involves "replacing itself"[14]. Although not clearly stated in the paper, "low" must mean low in relation to retail price, allowing the entrant to earn a positive profit on its retail product. By implication, therefore, competition at retail level must be imperfect and profits not competed to zero. For the entrant to have the incentive to invest its own network, its profits from that network must exceed the profits from renting the legacy network from the incumbent, taking account of risk.

Figure 9 shows the "replacement effect" where a low copper access price (combined with a relatively high retail price) creates a high degree of profitability for an entrant operating on the copper network. This creates an opportunity cost from loss of copper profits if investing in fibre, since customers will be moved from the copper network to the fibre network. This

[14] BCD (2012) footnote 5.

means that the NPV of the fibre investment must exceed the NPV of operating the copper business. The CLD indicates that once investment in fibre starts this may create a reinforcing loop for further investment since not only will reduction in copper customers impact the overall profits for the copper business, but also a smaller scale of operations for the copper business will likely reduce the profit margin per customer since some fixed costs will be spread amongst a smaller customer base, thus further reducing the opportunity cost.

Figure 9: Replacement effect described in Bourreau, Cambini, Doğan, 2012



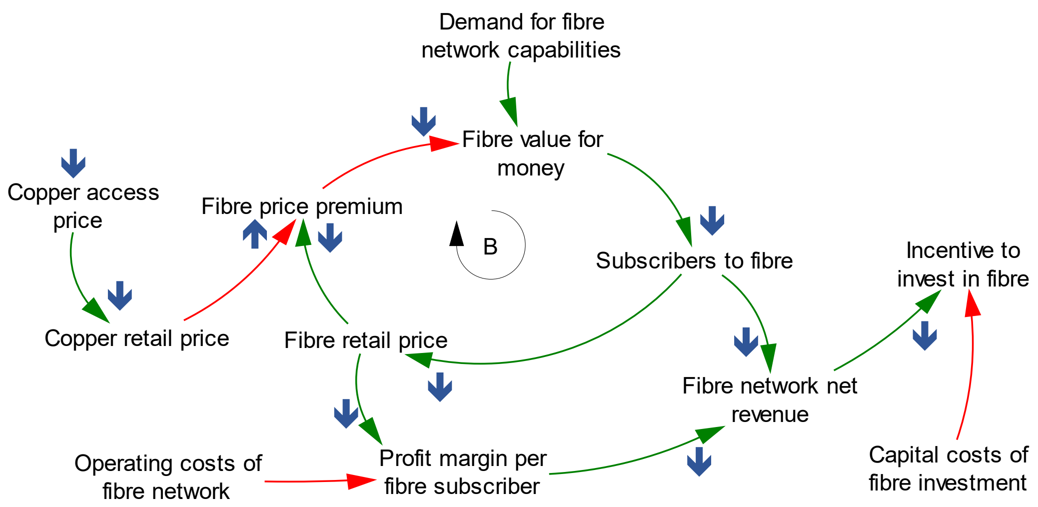
BCD also highlight what they term the "migration effect". This suggests that

> *"… if the access price to the [Old Generation Network] is low, retail prices based on that network are also low and hence, in order to encourage customers to switch from the "old" legacy network to the new network, the operator should also offer low prices for the [NGA]: this effect reduces the profitability of the new technology infrastructure, and hence, the incentives to invest in it."*

Figure 10 shows the migration effect, illustrating with the up and down arrows the impact of a low copper access price. The migration effect argument assumes that a low copper access price will lead to a low copper retail price (presumably due a high level of copper retail competition). The copper retail price is compared with the fibre retail price by consumers to determine value for money of fibre. If the price of fibre is too high compared to copper then value for money is low so there will be fewer subscribers to fibre. Operators are likely to lower the price of fibre to attract more subscribers to get the balance between subscriber numbers and price to maximise net revenue (shown by a balancing loop). Higher net revenue creates a better business case for fibre and so creates a greater incentive to invest in fibre, so the lower revenue for fibre will act as a disincentive to invest.

Alternatively, a higher copper access price (turning the arrow upwards) should lead to a higher copper retail price, and so allows a greater fibre retail price without increasing the price premium. Also, higher demand for VHCN network capabilities compared with the copper network will allow a higher fibre price premium since the capabilities will be valued more highly and there will be a greater willingness to pay.

Figure 10: Migration effect described in Bourreau, Cambini, Doğan, 2012



BCD suggest that their most interesting finding is that "regulators cannot treat the two access prices to the two different technologies independently".

There is an additional dimension to this question not discussed in BCD, which is that renting access from the incumbent operator gives the entrant optionality, whereas an investment in its own network is irreversible. This makes a significant difference under conditions of uncertainty. The effect of optionality on investment determinants will be discussed later in this review.

In another paper, Bourreau, Cambini and Hoernig (2012) find that high access charges for legacy networks encourage investment by entrants as they have lower opportunity costs. Entrants are expected to seek to reduce high variable costs of access with their own fixed costs, if they are able to earn a higher margin from their own network. Like BCD, they point out that the incentives to invest in NGA are not only influenced by the terms of access to fibre infrastructure but also by terms of access to legacy copper networks.

The interrelationship between low wholesale access prices to the legacy network and a disincentive for entrants to invest is also found by Grajek & Röller (2012)[15]. They develop an

[15] The authors acknowledge financial support from Deutsche Telekom.

econometric model based on a series of three equations that analyse the relationship between regulation and investment in infrastructure by incumbents and entrants.

The first equation measures whether the regulator is responding differently to investments by incumbents or entrants when making a change in the strength of regulation on the parties (what they term "regulatory intensity"). Grajek and Röller (2012) derive their measure of regulatory intensity from Plaut Economics' regulatory index (Zehnhäusern et al 2007), which covers a range of regulatory measures including the existence of an accounting separation obligation, regulation regarding full unbundling, line sharing, bitstream access, and subloop unbundling of fixed-line incumbents' local loops.

The second equation then examines the extent to which a change in investment by the incumbent is dependent on a change in the level of investment or in the stock of entrants' infrastructure.

The third equation performs the same estimate but for entrants, using regulatory intensity and the stock of incumbents' infrastructure as explanatory variables.

The results are estimated using panel data on more than 70 fixed line telecoms operators in 20 EU Member States during the period 1997 – 2006.

Grajek & Röller (2012) test for the endogeneity of regulation (the extent to which regulation is determined by the level of infrastructure investment) and investment decisions, which they describe as "a crucial part of the analysis often absent from previous studies" (p. 206). They used two different methods of estimating the equations, where one does not account for endogeneity and the other does[16]. They conclude that:

> *"…if we do not account for endogeneity of regulation, we find no significant impact of regulation on investment, whereas if we allow regulation to be endogenously determined by the level of investment, we find a significant effect" (p. 206).*

A second interesting finding is the different effects of investment by the incumbent and the entrant on regulation. The estimation finds that intensity of regulation increases with the stock of incumbents' infrastructure. They say that this finding suggests that regulators are subject to a commitment problem:

> *"When the level of incumbents' infrastructure stock is high, national regulators tend to grant easier access, which is a disincentive for incumbents to invest in the first place"* (p. 207).

[16] Ordinary Least Squares (OLS) and Instrumental Variable (IV) respectively

The authors also find that an increase in regulatory intensity, usually translated as lower access prices to the incumbent's network, increases the total investment (measured as stock of tangible fixed assets) across all entrants. They say that such an increase could be attributed to an increase in the number of entrants, larger investment by each entrant, or both. They therefore examine the effect at an individual entrant level and find that the impact of regulation on an individual entrant's investment is negative[17]:

> "…*which suggests that entrants' total investment increases even as investment by individual entrants declines with regulation that ease access. In other words, easier access pushes entrants toward service-based competition [as opposed to facilities based competition that requires higher levels of investment per operator].*"

The causal effects found in Grajek and Röller (2012) are interpreted as a CLD in Figure 11 below. A high intensity of access regulation provides easier wholesale access and so in increased number of entrants using wholesale access, which in turn leads to the potential for increased aggregate investment by entrants. However, the average level of investment per entrant declines due to higher expected retail margins for access seekers creating a greater opportunity cost of investing in their own infrastructure, which creates a balancing loop that slows the investment rate.

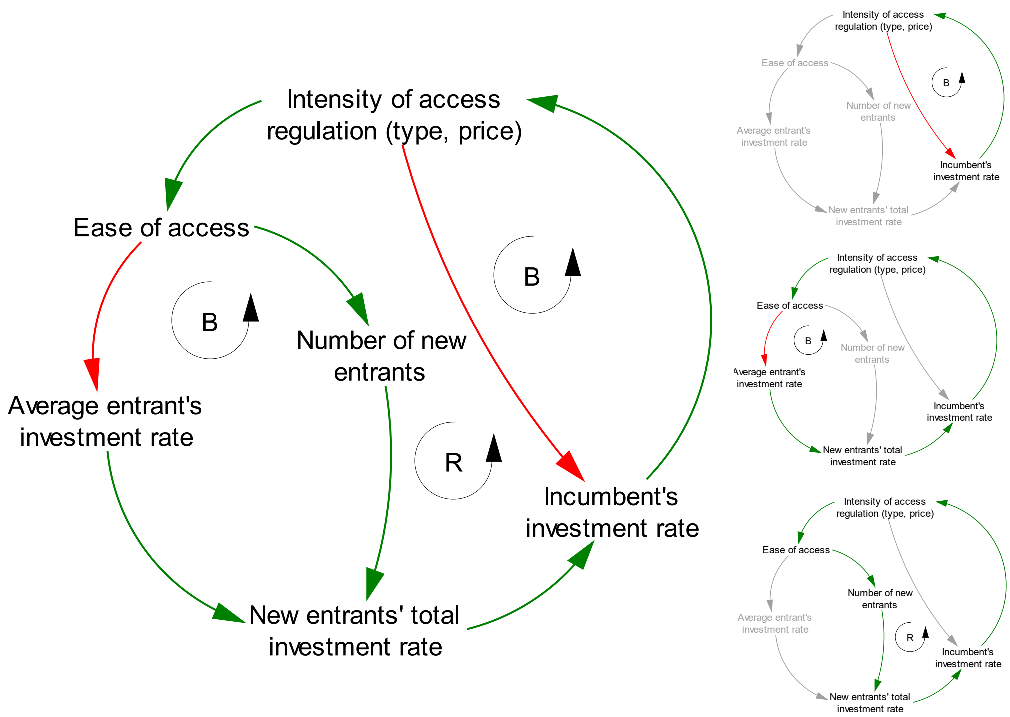
At the same time, however, the increasing total investment by new entrants increases the incumbent's total investment rate as a response to competition, which, according to Grajek & Röller (2012) causes regulators to increase the intensity of regulation. More intensive regulation would, ceteris paribus, decrease the incumbent's investment.

There are three competing feedback loops (as identified by the R (Reinforcing) and B (Balancing) symbols with the actual routes for those loops highlighted by the small insert diagrams. These loops are (from top to bottom in the insert):

- Balancing loop between incumbent's investment and intensity of access regulation since investment should increase the incumbent's market share, resulting in more intense regulation which then discourages investment.
- Balancing loop involving ease of access reducing the average entrant's investment rate, reducing responsive investment by the incumbent and so easing intensity of access regulation.
- Reinforcing loop involving ease of access increasing the number of entrants on the ladder of investment, increasing total entrant investment rate, which triggers more investment by the incumbent and so increasing intensity of access regulation, leading to easier access and further entrants.

[17] But note that this is only statistically significant at 10%.

The actual impact of those three competing loops on incumbent investment rates and intensity of access regulation will depend on which loops win out.
Figure 11: Causal Effects found in Grajek & Röller (2012))



It is possible, of course, that an increase in service-based competition influences investment rates by raising the appeal of VHCN-based services and thus speeding the capture of subscribers. It is also possible that easier access is a disincentive for the incumbent to invest. However, neither mechanism is noted in the paper.

Hellwig (2014) supports these views. Based on a comprehensive review of both theoretical and empirical literature, he concludes that the access prices for both the old and new networks have to be “carefully set” to induce investment at the socially optimal level. A low access price on the old network leading to a low retail price makes consumers less willing to switch to the new network, hampering investment. A high access price for the old network (relative to retail prices) aimed at incentivising entrants to invest in new infrastructure can disincentivise incumbents to invest due to lost wholesale revenue for the old network and fear of triggering investment by entrants. Relative access pricing for the new network must also be carefully considered:

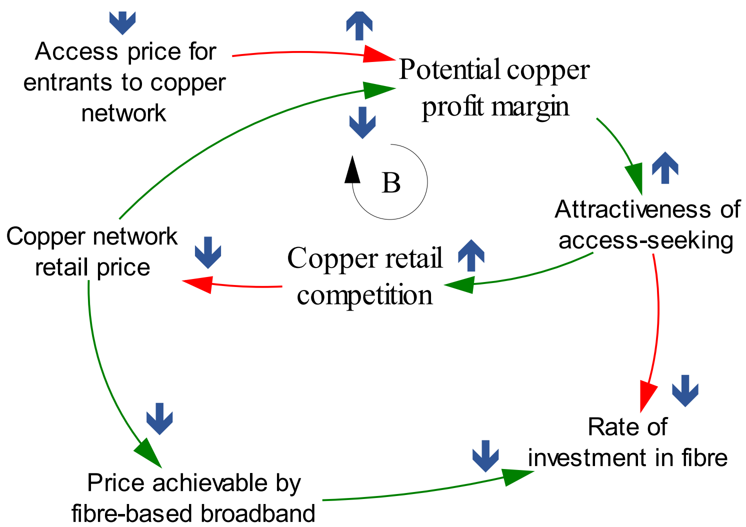
> *“…a low access price [for the new infrastructure relative to the old infrastructure] could hamper investment as firms then find access-seeking more attractive and the potential first mover would accordingly invest less” (p.69)*

Cave (2014) summarises the effect of copper unbundling on fibre investment:

> *"Clearly, unbundling which forces down the price of copper broadband is likely to have a restraining effect on fibre investment, by reducing the price of current generation broadband and thus the price which owners of fibre networks can charge. However (…) copper access decisions are mostly irreversible by now: policy makers and regulators must now lie upon whatever unbundled copper bed they have made."* (p. 679)

In Figure 12 a lower access price to the copper network increases the attractiveness of access-seeking which reduces the rate of investment in fibre since there is a higher opportunity cost from customers moving from the copper network over to the fibre network (i.e. losing retail revenue from customers on the copper network). The attractiveness of a lower access price to the incumbent's copper loop increases retail competition which ultimately reduces the retail price for copper (a balancing feedback loop since lower retail prices will start to reduce the attractiveness of access seeking to new entrants). In turn the lower copper retail price reduces the prices achievable by fibre broadband, assuming that the price of copper access has some restraining effect on fibre prices. Lower prices for fibre, in turn reduce the rate of investment in fibre access. Note that this is very similar to the migration effect shown in Figure 10.

Figure 12: The Effect of Lower Access Prices to Legacy Networks on Investment in NGA



On the other hand, low profits on current generation networks create incentives to invest in next generation networks, but only if there is sufficient profit from the next generation network to overcome lost profits from services based on access to the old network.

2.2.2 Incumbent's Indirect Costs

Just as the entrant faces indirect costs from regulation, so too does the incumbent. The same authors have researched these regulatory costs on the incumbent.

There have been a number attempts to distil regulation down to a single variable and measure the effect of that index variable on investment. Hellwig (2014) reports on three other studies (Friederiszick et al 2008, London Economics and Price Waterhouse Coopers 2006, Cadman 2007) and finds the results "ambiguous" and dependent on the addressee of the study. Cave (2014) describes the Grajek & Röller (2012) findings as "suggestive, but not conclusive" (p. 677): a description that may also be applied to the other papers referred to by Hellwig.

As discussed earlier, Grajek & Röller (2012) find a causal relationship between the increase in non-price regulatory intensity and a reduction in incumbents' fibre investment.

> *"To be specific, our estimate suggests that increasing regulatory intensity by 0.5, which roughly corresponds to the average change in the regulatory regime in the EU15 between 1997 and 2002, reduces incumbents' infrastructure stock by approximately 49 percent and by as much as 72 percent in the long run." (p. 207)*

Inderst and Peitz (2012) examine market asymmetries between incumbent and entrant firms. Using a base case of marginal cost, they find that when the incumbent firm is required to set access prices above marginal costs, its incentives to invest are less than those of the access seeking entrant. Whereas a high access fee for the old infrastructure lowers the entrant's opportunity costs, the incumbent's are raised, as it will lose any profits it earns from access to its legacy network. This is the analogue of the findings discussed above: the incumbent may lose profits from the legacy network by investing in a new network and so will not wish to do so.

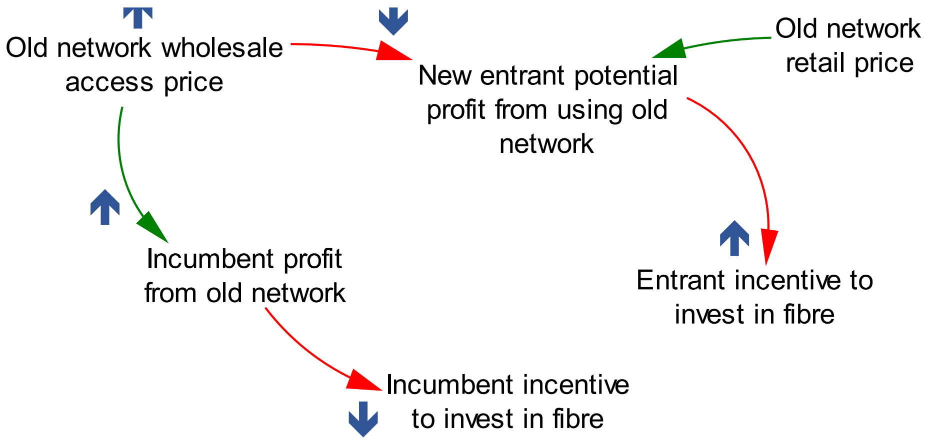
Figure 13 shows the effects of an increase in the wholesale access price to the current generation network on investment incentives of the incumbent and entrant. If the wholesale access price is increased, the incumbent can earn more profit from the current network and so has a reduced incentive to invest in fibre as the opportunity cost of so doing is increased. By contrast, the new entrant may earn less profit from access seeking and so have an incentive to invest in fibre access as its opportunity cost reduces.

Bourreau, Cambini and Hoernig (2012) summarise what they describe as a "vibrant academic literature" on the subject by stating:

> *"…all the papers stress that the incentives to invest in NGANs differ between the historical operators and the new entrants. Incumbents may prefer not to invest in a*

new infrastructure and thus to slow down the migration, especially (but not only) when the access price to the old network is well above costs." (p. 403)

Figure 13: The Effect of High Access Prices to Legacy Networks on Investment in NGA



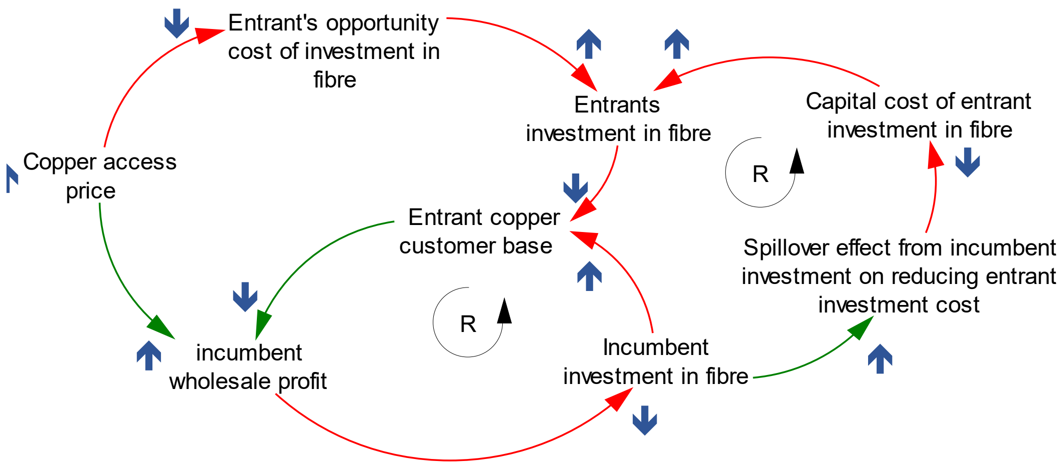
The incumbent, therefore, faces a similar investment rule to the entrant. Any profits it earns from the new network need to produce a positive NPV in their own right and exceed any lost profits from selling wholesale access. Bourreau, Cambini, Doğan (BCD) (2012) refer to the "wholesale revenue effect" where a high access price provides the incumbent with high revenue from entrants' access to the Old Generation Network (OGN). This results in an opportunity cost from investing in a NGA network, so that the NPV of the new network investment must exceed that of the old network. They further point out that the incumbent risks triggering entrants to build their own Next Generation Access network in retaliation, losing wholesale revenue for the incumbent for both its old and new networks. Spillover effects from the incumbent's investment in the new network can reduce the costs of the entrants investment (e.g. planning and wayleaves, repairing ducts, in-building wiring) so making investment more attractive.

Figure 14 shows that a high copper access price (indicated by the up arrow) contributes to higher copper wholesale profit for the incumbent, which creates an opportunity cost for investment in a fibre network, reducing the incumbent's incentive to invest in fibre. Investment in fibre will reduce the entrant's copper access customer base (either moved to fibre access or lost) reducing the wholesale profit and, therefore, the opportunity cost for the incumbent. This creates a reinforcing loop since once investment in fibre by the incumbent has started the profitability of copper access will be reduced, opportunity cost will be reduced, and the incumbent has more incentive to invest in fibre.

Investment by the incumbent may cause retaliatory investment by entrants (either due to access restrictions or high access costs). Two impacts make investment by entrants more attractive: i) high copper access prices (assuming this indicates lower profit margin) mean that the entrant's replacement cost is lower (i.e. the opportunity cost of moving customers from copper access to their own fibre infrastructure); ii) Spillover effects from the first-mover incumbent makes the capital cost per premises passed lower for the entrant, improving the NPV for fibre investment. This is a reinforcing loop since entrant investment in fibre reduces the wholesale revenue opportunity cost that restricts incumbent investment in fibre, which further encourages entrant investment in fibre.

The two reinforcing loops mean that an incumbent will be less willing to invest and trigger an escalation of investment that damages its copper wholesale profitability.

Figure 14: Wholesale revenue effect described in Bourreau, Cambini, Doğan, 2012



One potential problem with these models, however, is that they do not consider any change in the retail market as a result of moving from legacy to next generation networks. The incumbent may see the investment in fibre as having two purposes. First, it has an intrinsic value, i.e. the positive cash flow it will earn from the investment. Secondly, the investment may be used to raise entry barriers for rivals and so realise a strategic value from the investment. This possibility has been noted in Cadman (2019) in the context of vertical separation and integration. He notes the strategic value of an investment by a vertically integrated firm is derived from that investment's ability to favour its own downstream business to the detriment of rivals.

The regulator, therefore, faces a dilemma: does it force access prices to the legacy network down, which promotes static efficiency and may encourage the incumbent to invest, or does it set access prices above cost, discouraging the incumbent from investing but encouraging the entrant? This is the classic trade-off that has been highlighted in much of the literature (Grajek & Röller, 2012).

Charles River Associates (2012) provides a comprehensive review of the literature on the incentives of a copper incumbent to invest in a fibre network and identify two "effects". First, the "replacement effect" by which the incumbent will treat revenue from copper as an opportunity cost with respect to investment in fibre: the incumbent may see fibre as cannibalising its existing copper revenues. This suggests that high copper prices act as an investment deterrent. Secondly, the "business migration effect", which is the extent to which copper and fibre networks operate in parallel and the copper prices constrain fibre prices. If the access price for copper is low, wholesale customers will also require a low price for fibre access, such that investment in fibre may not be profitable.

They conclude by stating:

> *"Overall, it is thus not clear in terms of principles whether lower access prices for copper should encourage investment in fibre. The existing literature however suggests (unsurprisingly) that, for any given access price for copper, an increase in the access prices for fibre will spur investment. This literature also suggests that access prices for copper and fibre should be positively correlated." (*p. 63)

Various solutions have been put forward to find a way out of this dilemma, including the European Commission Recommendation on non-discrimination and costing methodologies (European Commission 2013), which supersedes much of the literature referred to above. The Recommendation suggests that any costing methodology used by NRAs should "provide a clear framework for investment and be capable of generating cost-oriented wholesale copper access prices serving as an anchor for NGA services" (Recital 25). The Commission's view is that that a Bottom Up LRIC model based on a modern efficient network (i.e. a fibre network) would provide the correct build-buy signals and therefore the right incentives or investment.

BCD propose that, where the incumbent has larger NGA coverage than the entrant, the regulator has to set an access price for the new infrastructure that is positively correlated with the access price to the legacy network. They suggest that such positive correlation will favour migration at the wholesale level. However, where the entrant has a larger NGA network, the reverse is true. The access price to the legacy network should still be low, but a higher price should be set for the NGA network controlled by the entrant to incentivise investment by both the entrant and incumbent.

Ofcom (2007) put forward an alternative approach: anchor product pricing. Under this approach the regulated operator offers one or more products on the next generation access network to end-users with prices and service levels that are the same as an anchor legacy product for a period of time. For example, there could be a product on the fibre network that is equivalent to a copper service, such as ADSL offering 24Mbps broadband access. Outside of these regulated anchor products, prices for higher performance or new service offerings would not be subject to price control. This allows the regulated firm the freedom to set prices for "new" services but it would not be able to exploit a monopoly position (should it have one) as these prices will be to some degree constrained by the regulated price of legacy products. Ofcom says:

> *"In effect, only a few prices in the value chain are fixed by regulation. Prices of other products would be set by the access network owner in negotiation with its customers, including its own downstream divisions."* (Ofcom 2007, p. 41)

Anchor product pricing appears similar to BCD's proposal for allowing higher access charges for NGA where the entrant has the larger network. In both cases, the anchor product constrains the ability of the firm controlling NGA to set prices too high if such a high price would not be profitable due to consumers remaining with, or switching back to, the legacy product. However, the NGA owner would be able to extract the maximum profit it can and therefore be incentivised to invest if there is a perceived superiority by consumers of the NGA product.

NERA Economic Consulting (2017) reviews a scheme proposed by Vodafone referred to as the "copper wedge". This wedge refers to a gap between the price charged to access seekers for copper network services and the price received by the infrastructure owner. Access seekers pay more than the incumbent receives, which should provide the necessary incentives to invest in fibre networks. The difference can be used by the regulator for other purposes, such as contributing to a universal service fund. NERA describes the "innovation" of wedge pricing "is that it allows each price to be set at a level that incentivises economically efficient conduct by all parties".

Nitsche and Wiethaus (2011)[18] examine different regulatory regimes and rank them according to their effect on investment in Next Generation Access networks. In particular they compare the Long Run Incremental Cost (LRIC) regime with Fully Distributed Costs (FDC), risk sharing or joint investment and regulatory holidays.

The main ingredients of their model are a regulated access price linked to costs and uncertainty. The model has two stages where the incumbent first invests in an NGA network and, secondly, the incumbent and entrant compete in the retail market. The entrant's access to the new infrastructure is known to be regulated by one of four regulatory regimes: Long Run Incremental Cost (LRIC); Fully Distributed Costs (FDC); risk sharing or joint investment and regulatory holidays. The model includes a risk that consumer willingness to pay does not

[18] The authors of the article acknowledge the help and support of a number of individuals and organisations, including Deutsche Telekom.

outweigh the cost of investment, thus returns are unknown due to demand side risk.

They find that FDC or a regulatory holiday are most conducive to investment. FDC allow the regulated firm to recoup the NGA investment costs through the access price, regardless of NGN's market success. In this sense it is like a regulatory holiday, which would allow the incumbent that invests in NGA to enjoy a period where it does not have to provide access to entrants. It would, therefore, only face competition in retail markets if there were an alternative network that bypasses the incumbent's. Both FDC and a regulatory holiday potentially allow the incumbent to earn profits above the cost of capital.

This contrasts with LRIC:

> *"The aim of LRIC regulation is to mimic competition. The incumbent may recoup investment costs through the access price as long as the asset reflects the most efficient technology in providing the service. NGA will be considered an efficient technology if the majority of consumers value NGN-based services; otherwise the copper network is (or would be) the cheapest way to provide old services."*

Thus if NGA is not commercially successful, and the access price is based on LRIC, the incumbent will not be able to recoup its investment. Knowing this, the incumbent is unlikely to make the investment in the first place.

3 Cash Flows

The second element of the NPV equation is the cash flow from operations, which is strongly affected by demand, but may also be affected by operating costs, i.e. if the operating costs of a new investment are sufficiently low, this may lead to a positive NPV even if demand is unchanged. Fibre is generally accepted to have lower operating costs due to greater reliability. However, as this is a feature of the technology and out of the control of the regulator, it is not covered in this literature review.

This section of the review, therefore, considers papers that are concerned with demand and is divided into three sub-sections. The first sub-section examines socio-economic drivers of demand. The second reviews papers concerning direct drivers of demand and the third with policies that promote competition, which in turn affects demand and so feeds through to investment. Competition may have a positive effect on demand but may reduce available profits.

3.1 Socio-Economic Drivers of Demand

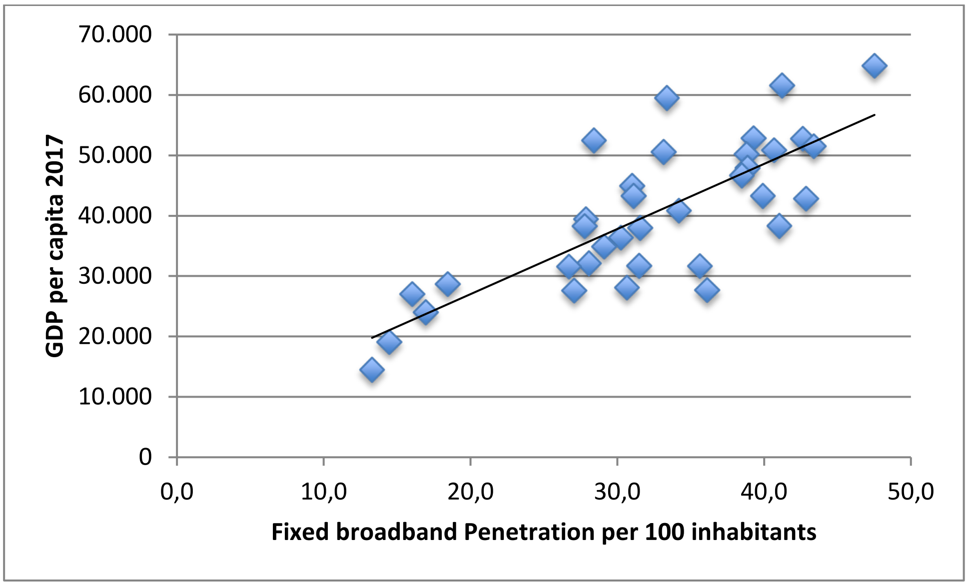
Whilst much of this literature review is concerned with what sector policy makers can do through regulation to promote investment, socio-economic drivers are likely to play an important role on the demand side and so we have reviewed some of the relevant literature here. Most of the research to date studies the socio-economic drivers of broadband demand in general, rather than a specific generation of access or technology. Although these drivers are outside the control of the NRA, they are important and are discussed in the literature.

Intuitively it could be expected that household income is likely to have a positive effect on broadband adoption rates, and this indeed has been found to be the case, although it should be noted that these are findings of correlation rather than causation. De Ridder (2007) finds that four of the five studies he reviews identify a positive and significant link between income and penetration (Garcia-Murillo & Gabel 2003, Wallsten 2006, Grosso 2006 and Turner 2006). Lin and Wu (2013) confirms this, finding that income and education are key determinants of broadband adoption in OECD countries.

De Ridder finds one dissenting paper (Kim, Bauer & Wildman 2003) and himself finds that the link between GDP per capita and broadband penetration was not statistically significant. He says his own findings are "surprising" and that future research should consider a larger data set.

Lemstra (2016) examines the determinants of broadband supply and demand in twelve European case studies reported in Lemstra and Melody (2015) to establish determinants of supply and demand of broadband in Europe. He finds strong correlation (0.748)[19] between the ability to pay, measured as Gross Domestic Product (GDP) per capita, and take up of broadband. This is illustrated in Figure 15, which shows the correlation between GDP per capita and broadband penetration in OECD countries (excluding the two outliers, Luxembourg and Ireland) in 2017.

Figure 15: Relationship between GDP per capita[20] and Fixed Broadband Penetration



Source: OECD data. Authors' Analysis

Lemstra states:

> *"The willingness to pay of end-users relates to the socio-economic setting. The use of the Internet, and thus the need for broadband, is closely related to the penetration of personal computers. This in turn is closely related to educational and income levels. Furthermore, the use of the Internet by consumers for e-commerce and for e-government is directly related to the degree to which business and governments have embraced the 'net' in their business model."* (p. 10)

Ford, Koutsky & Spiwak (2007) employ a cross-section regression model for the states of the USA to establish the effect of various socio-economic endowments on adoption rates.

[19] This is a stronger correlation than is found in the authors' analysis of the same variables in the OECD, which is 0.58. However, if two GDP outliers are excluded (Ireland and Luxembourg), neither of which are in Lemstra's sample, then the coefficients are remarkable similar: 0.748 in Lemstra and 0.777 in the OECD sample.

[20] US Dollars at Purchasing Power Parity, current prices 2017.

Amongst the 14 endowments they test are income, income inequality (measured by the Gini coefficient[21]) and whether the household has a member in school. They find a significant relationship between income and adoption that suggests a 10% increase in income leads to a 3.8% increase in adoption. Grosso, in his 2006 assessment of OECD countries, finds a much stronger effect. He states:

> *"A one per cent increase in GDP per capita leads to an increase in broadband penetration of 5.5 per cent. As explained earlier, a coefficient larger than one would suggest that broadband is a superior good and consumption of broadband is likely to increase at a greater rate than an increase in income. The above result confirms the a priori expectations of the relationship between income and broadband penetration."* (p. 17)

Ford et al (2007) also examines other socio-economic variables. They find that income inequality and school have much stronger effects that income. They estimate that a 10% reduction (rise) in inequality is associated with a 15% increase (fall) in broadband adoption and that a 10% increase in the number of households having a member at school is associated with a 28% increase in broadband adoption.

By contrast, American States with a high proportion of retirees and a larger percentage of rural and farm areas have lower levels of broadband penetration than urban states where there are fewer retirees.

The general consensus is that income, normally measured as GDP per capita, is strongly and positively correlated with demand for broadband, albeit the literature to date does not distinguish between generations of broadband. It is not therefore possible to tell whether income may have a different effect on the demand for VHCN and therefore the investment decisions of operators.

3.2 Direct Drivers of Demand

Understanding what drives consumer demand is critical, for without demand there is no positive cash flow and so no investment will be made. However, the empirical evidence of such drivers is rather scant (Abrardi and Cambini 2019).

BEREC (2016) considers demand side factors and find that

> *"the majority of Member States (…) report on a lack of demand and willingness to pay for very high-speed capacity broadband products. This in turn has an effect on*

[21] An index of income equality on a scale 0 – 1. A Gini coefficient of 0 would mean everyone earns the same and of 1 would mean one person has all the earnings.

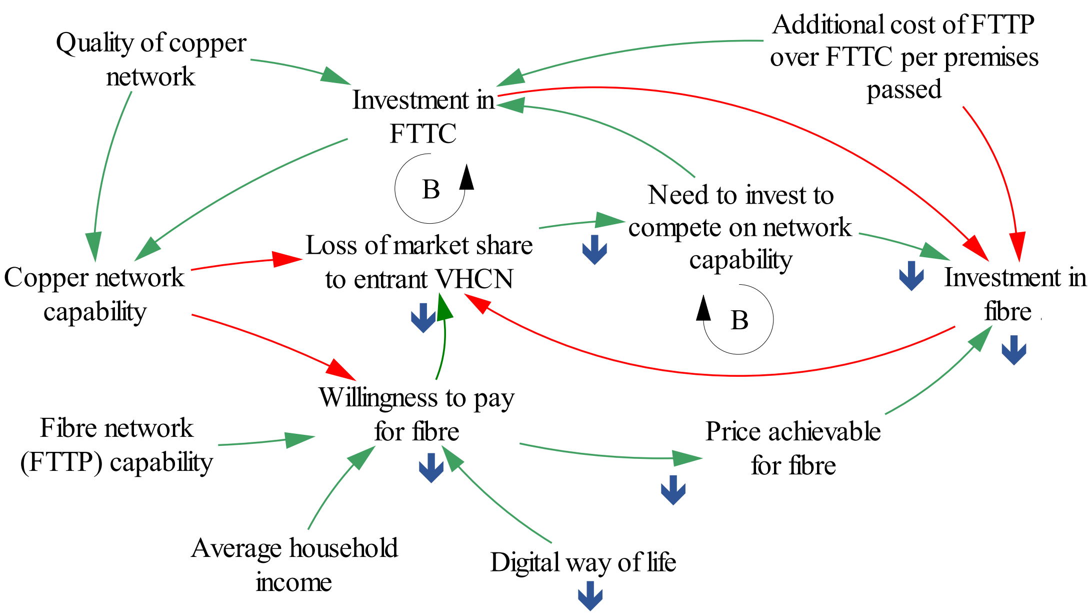
the business case of operators when rollout decisions are being evaluated and consequently on both the pace of rollout and on the technology mix of the rollout (e.g. FTTC vs FTTP)" (p. 14 – emphasis in original).

BEREC attributes this lack of demand to a lack of willingness to pay a price premium for NGA-based services compared with copper based services. In economic terms, they suggest the marginal utility from NGA is less than the marginal price.

In Figure 16, a low "Digital way of life" leads to a low willingness to pay for fibre, which will limit the price premium achievable by fibre compared with the copper network. A lower price for fibre will limit revenues from fibre and so reduce the incentive to invest in fibre. An incumbent may still be willing to invest in fibre if VHCN entrants enter the market and start to impact market share, but a low willingness to pay for fibre will limit the speed at which competition from entrants occurs.

The BEREC quote also notes the mix between FTTC and FTTP. A low willingness to pay for fibre will limit competition to copper networks, but if competition does occur (say from incremental increase in speeds offered by cable) then, provided that the quality of the existing copper network allows it, the incumbent may choose to upgrade to FTTC rather than directly to FTTP. Relative costs of FTTC and FTTP upgrades and the price achievable for fibre will affect the business decision on the upgrade route. Investing in FTTC will reduce the capability difference between copper and fibre, reducing the willingness to pay a price premium for fibre and reduce pressure on copper market share, reducing incentives to invest in fibre by both entrants and incumbent.

Figure 16: How Digital way of life and willingness to pay for fibre affects investment



Referring to demand from households, BEREC suggests that a "digital way of life or e-culture", such as that found in Scandinavia, and higher levels of income and educational status are drivers of demand as in these countries and so consumers consider the marginal utility to be greater than the marginal price. In Figure 16, if "Digital way of life" is high (reversing the down-arrow to an up-arrow), as found in Scandinavia, then this propagates through the diagram reversing all of the arrows to become up arrows. It makes it more likely that both entrants and incumbents will invest in fibre since the revenue side of the business case for fibre will be improved.

Bourreau, Feasey and Hoernig (2017) (BFH) provides a comprehensive review of demand side policies designed to accelerate the transition to ultrafast broadband. They first identify four policy measures that have been adopted by various governments to promote standard broadband. These are:

I. Policies to promote the use of devices. These include the direct provision of devices to qualifying homes, the provision of subsidies and the provision of tax benefits.
II. Policies to promote the development of services and applications, such as e-government.
III. Policies to promote digital literacy and skills.
IV. Policies to reduce the direct price of broadband connections for those homes that do not have one, including the adoption of 'affordable tariffs' for basic broadband products.

BFH report that there has been little empirical study of the effect of demand side policies on take up, but do report a study by the Florence School of Regulation (FSR) conducted in 2011 (FSR 2011) that found four demand-side measures that had a statistically significant and positive impact on broadband adoption levels. These were:

I. Demand aggregation policies (these are policies that require households to commit to purchasing broadband connections within a given timescale).
II. Direct subsidies.
III. Promotion through e-government services.
IV. Promotion of 'private demand', which BFH say may include the promotion of digital literacy.

FSR also found that demand side measures become more effective as adoption rates rise.

BFH identify four categories of households and the demand side measures for ultrafast broadband that are appropriate for each category. These are presented in a table reproduced below.

Figure 17: Demand Side Interventions Matrix

Can't pay and won't pay Exposure to Ultra Fast Broadband (UFB) services outside of the home (schools, libraries) to improve willingness to pay. Will require introduction of UFB 'social tariffs' in the longer term.	**Can pay but won't pay** Exposure to UFB services outside of the home (schools, libraries) to improve willingness to pay. Promote demand-side aggregation measures in order to promote adoption and reduce supply-side risks.
Can't pay but will pay Will require introduction of UFB 'social tariffs' in the longer term.	**Can pay and will pay** No basis for public interventions.

(BFH, 2017 p62)

BFH also comment on three specific policies. They are "not surprised" to find that **demand aggregation** measures "produce large effects in terms of broadband adoption". However, the authors are surprised that this policy has not been more widely adopted in the EU, with only the Netherlands and the UK encouraging such schemes in the past although the impacts of these policies are not reported in the paper.

BFH comment that the European Commission has generally sought to avoid **social tariffs** and similar universal service type policies in the broadband market, perhaps because of fears that such schemes may distort competition. National policymakers may be concerned that any subsidy may require a long term financial commitment and that such schemes in the past may have been open to fraud or been poor value for money.

The Code does make provision for Member States to offer special tariffs for consumers with particular needs (Art. 85). At the time of BFH wrote their article, the Code had not been adopted and the authors were therefore "not clear whether or not the Commission's proposed changes to the Universal Service arrangements will lead to their greater use by Member States to overcome affordability barriers to the adoption of either basic broadband or UFB" (p. 58). At the time of writing it is still only a few months since the Code was adopted by the Council and Parliament and so that statement would still stand.

The third set of measures are aimed at **increasing consumers' willingness to pay (WTP)**. The authors are somewhat sceptical about the effectiveness of such policies, in particular in increasing demand for UFB, with two exceptions. First, efforts to expose users to UFB outside the home, in places such as schools and other educational institutions, are regarded as successful as UFB is an "experience good". Secondly, the use of demand aggregation policies could be just as successful in moving customers from standard to UFB as they were in encouraging demand for standard broadband and so increase WTP for UFB.

Abrardi and Cambini (2019) provides a useful summary of eight recent papers that has been partially reproduced below.

Authors	Main results
Belloc et al (2012)	The effect of demand-side policies is always positive and increases with the degree of development of the broadband market, while the effect of supply-side decreases as the market matures.
Lin and Wu (2013)	The key determinants of broadband adoption are income, education, and quality of the Internet content in the innovator and early adopter stage; platform competition and previous broadband penetration in the early majority stage; and broadband price in the late majority and laggard stage.
Calzada and Martínez-Santos (2014)	Downstream speed has a positive and non-linear impact on price, and that the price per Mbps of cable modem and fiber technologies is lower than that of xDSL.
Briglauer (2014)	The more effective previous broadband access regulation is, the more negative the impact on adoption, while competitive pressure from mobile networks affects adoption in a non-linear manner.
Haucap, Heimeshoff, Lange (2016)	An increase in tariff diversity has a positive and significant impact on broadband adoption.
Ovington, Smith, Santamaria, Stammati (2017)	LLU has a positive impact on broadband adoption, but with diminishing returns. In addition, LLU is less effective in enhancing broadband penetration in the areas where alternative networks already have a significant share of broadband lines.
Grzybowski et al. (2018)	Consumers value FTTH connections significantly more than DSL connections with speed of 1–8 Mbps. However, the valuation of FTTH has increased over time: at the beginning of 2014 FTTH services were

	valued only slightly more than DSL services. Switching costs are significantly higher when switching from DSL to FTTH.
Briglauer and Cambini (2018)	An increase of the access price to the legacy network increases both the adoption and the deployment of fiber-based technology, but the impact on the latter is stronger than on the former.

(Abrardi and Cambini, 2019)

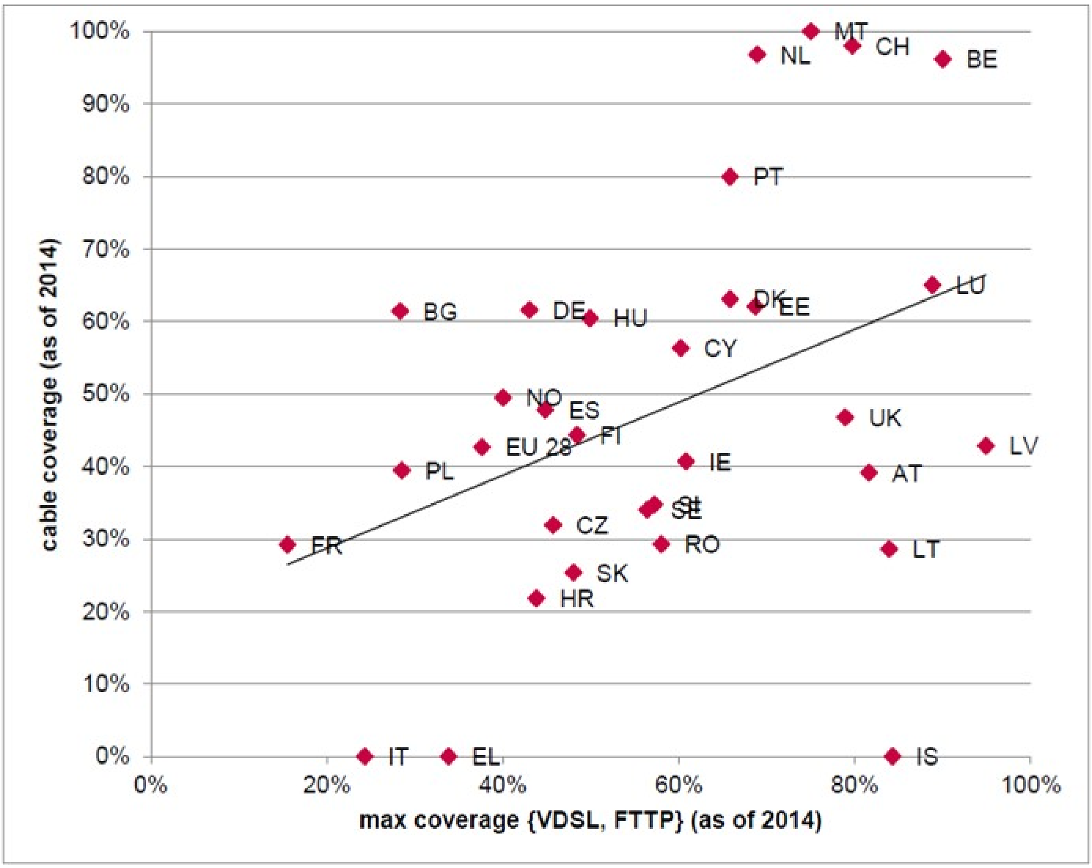
3.3 Competition

The effect of competition as a driver of demand, and therefore the cash flow element of the NPV equation, is another area that has been widely studied in the academic and wider literature. Two types of competition are widely recognised: service-based and facilities-based. The former is competition in retail markets provided by firms that use wholesale access to the incumbent operator's network, also known as access seekers. The latter is competition between firms that own their own networks and so are not reliant on the incumbent's network[22]. Such competition is mostly provided by cable operators, but there is an increasing number of independent fibre networks across the EU.

BEREC (2016) notes that a number of studies have shown facilities-based competition is "a main factor driving NGA deployment" (p. 12). BEREC provides a figure showing a positive correlation between cable coverage and coverage of FTTC/FTTP. Similarly, WIK Consult (2015) reports that DOCSIS 3.0 has had a positive impact on NGA coverage by the incumbent, although the data they present shows a correlation rather than proving cause and effect. They provide the graph presented below as Figure 18. BEREC (2016) suggests that incumbent network providers need to upgrade quickly to keep pace with offers from cable operators for higher bandwidth.

[22] Except for interconnection services, where users of one network need to communicate with users of another. This requirement is symmetrical.

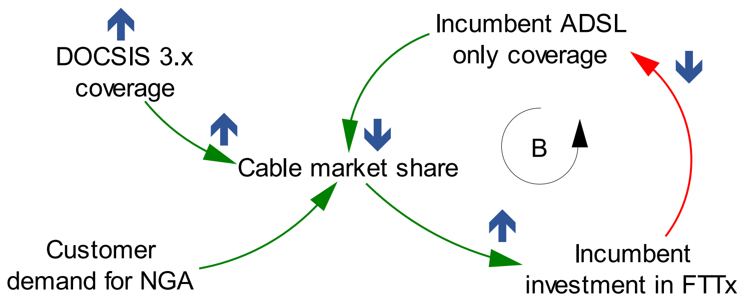
Figure 18: Impact of Cable on NGA Coverage



Source: BEREC (2016) p. 13

Figure 19 shows that investment by cable to DOCSIS 3.x can take market share from an incumbent's ADSL-only network, provided there is customer demand for NGA. Increased customer demand for NGA over time would increasingly chip away at the ADSL market share. The loss of market share, and therefore revenue, by the incumbent would encourage investment in some form of fibre, based on the relative capital costs of FTTP and FTTC and the ability of the copper network to be upgraded. This would reduce the incidence of ADSL-only coverage and reduce, halt or possibly reverse the cable market share growth.

Figure 19: Effect of Cable Competition on Roll-out of Fibre



Hellwig (2014) reviews various papers that cover the effect of competition on broadband penetration and on fibre deployment. The papers reported show overwhelmingly that facilities-based competition has stronger and more positive effects on penetration and deployment than service based competition.

Figure 20: Papers Reporting Positive Effect on Broadband Penetration by Type of Competition

Facilities based competition	Service based competition
Bouckaert et al 2010 Cincera et al 2012 Dauvin & Grzybowski 2014 Distaso et al 2006 Höffler 2007 Nardotto et al 2012	Gruber & Koutroumpis 2013

Author's summary based on Hellwig 2014

Figure 21: Papers Reporting Positive Effect on Fibre Deployment by Type of Competition

Facilities based competition	Service based competition
Briglauer et al 2013 Briglauer 2014 Wallsten & Hausladen 2009 Waverman et al 2007	

Author's summary based on Hellwig 2014

In a more recent paper Bourreau, Grzybowski & Hasbi (BGH) (2018) explore the effect of unbundling on entry into fibre based on a panel of 36,104 municipalities in France over the period 2010 – 2014. Two models of entry are studied: (i) alternative operators using wholesale access to the incumbent's legacy copper network via local loop unbundling (LLU) and (ii) the incumbent and two alternative operators using the fibre technology[23]. They develop two econometric models, one for LLU entry and one for fibre entry.

The LLU model is an entry threshold model that seeks to explain the profit of an entrant having *n* competitors in each local market as a function of the size of the market, the negative effect on profits from the n^{th} firm and a number of other local variables. From this they deduce three inequalities that cause net entry, inaction or net exit. Finally, the three inequalities are combined using the profit specification to derive the probability of observing entry at any given time. A similar approach is used in the fibre model. However, the authors admit that due to the small number of municipalities with fibre they do not observe any sunk costs and do not observe any exit. Therefore, the evidence of entry thresholds may be biased in this model.

The key finding of the paper is that "a higher number of LLU competitors, hence a less concentrated DSL market, makes fibre entry more likely" (p. 26). They explain this result:

> *"…by the vertical differentiation between fast broadband and basic broadband, which implies that a higher number of LLU competitors reduces less the profits obtained from fiber operations than the opportunity cost of investment due to lost DSL profits[24]. Furthermore, we observe in the data that fiber deployment by SFR and Free is always preceded by entry via LLU. In general, firms which have invested into LLU in an area have a lower incremental cost of investing into fiber"* (p. 26).

This finding supports a similar finding in BEREC (2016):

> *"It should also be noted that the alternative operators investing in an own fibre access network were often those which gained considerable economic size based on (LLU) access to the legacy network and had obtained a significant LLU presence (e.g. Free and Numericable-SFR in FR, Vodafone and Optimus in PT or Jazztel in ES). These are examples of how alternative operators used the ladder of investment to move up the ladder to deploy their own access infrastructure."* (p. 35)

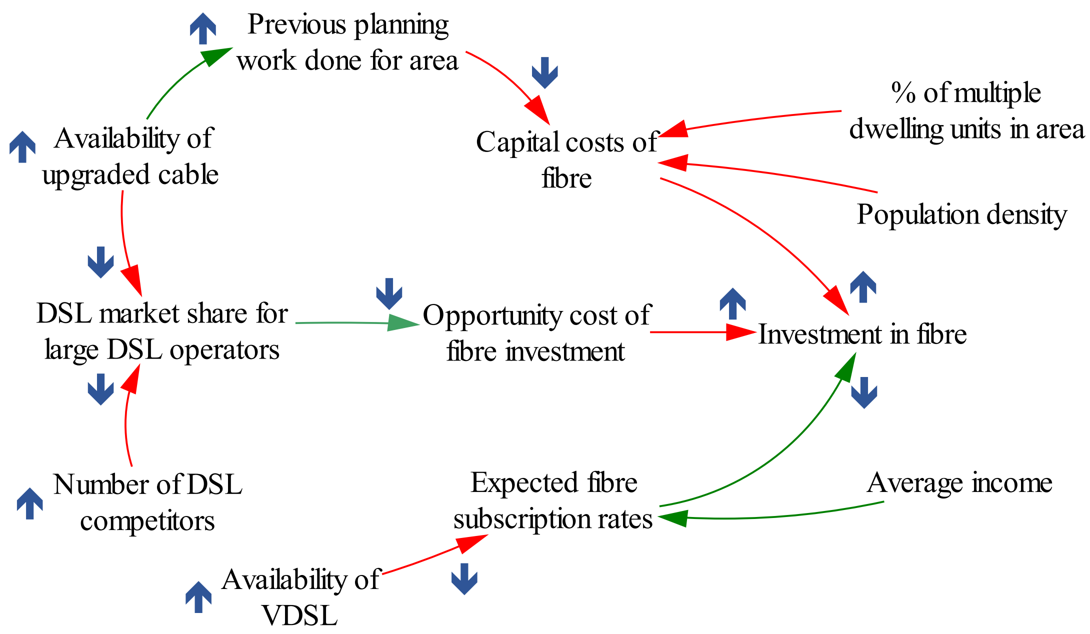
BGH also find that the presence of upgraded cable in a municipality has a positive impact on fibre deployment. BGH suggest that fibre entrants may also benefit from investment spillovers, which reduce the cost of rolling out fibre.

[23] It is not clear from the article if the alternative operators use the incumbent's fibre or build their own networks.
[24] The article does not make this point, but this opportunity cost appears similar to the migration and replacement effects noted earlier in this review.

The BGH paper is interpreted as a CLD in Figure 22 below, showing the impact of three market conditions:

i. A high number of DSL competitors reduces the market share of individual operators, with particular impact on the larger operators. The reduced market share reduces the opportunity cost of lost revenue from the copper network by investing in fibre and so encourages investment in fibre.
ii. The availability of upgraded cable in an area reduces the market share for DSL operators and so reduces the opportunity cost of investing in fibre. The planning procedures already carried out for upgrading cable could potentially reduce the planning and admin costs for deploying a new fibre network, and therefore reduce the capital costs for deploying fibre. Lower capital costs for fibre encourages the investment in fibre.
iii. Availability of VDSL reduces expected fibre subscription rates since it is a substitution product (at least for some consumers), which reduces the potential revenue for fibre and discourages investment in fibre.

Figure 22: Causal mechanisms identified in Bourreau, Grzybowski & Hasbi, 2018



Another recent paper asks whether competition in the DSL market matters for fibre penetration (Fourie and de Bijl 2018). This paper addresses the question of whether and how competition in the DSL market affects penetration of fibre networks (FTTH/B), which indirectly reflects investment incentives. They suggest that firms facing intense competition in the DSL market may invest to escape competition and propose that the relationship between market concentration in the DSL sector and fibre penetration follows an inverted U curve.

To test this hypothesis they draw on data from 27 European countries from 2004 – 2015 and use a fixed effects regression model with various measures of concentration in the DSL market and an Infrastructure Competition Index (ICI) to control for facilities based competition.

Before presenting the results of the regression, however, Fourie and de Bijl present the relationship between FTTx penetration and DSL market concentration graphically for each year from 2004 – 2015. They suggest that the figures are too ambiguous to draw any conclusion. However:

> *"One can (…) observe that countries that have severe competition (reflected in a low HHI) or very little competition (reflected in a high HHI) in the DSL sector have a low degree of fibre penetration. Countries that have an intermediate degree of competition in the DSL sector appear to have relatively higher levels of fibre penetration."* (p. 786 – 787).

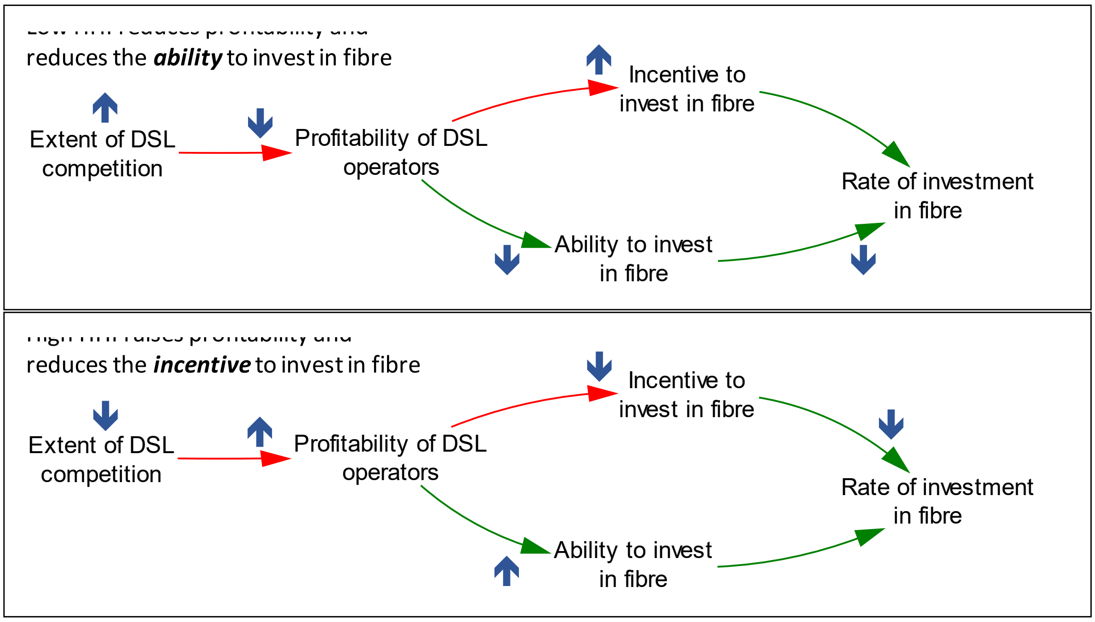
However, some countries that have a near monopoly at retail level in the DSL market also have high levels of fibre penetration.

Fourie and de Bijl run six versions of their regression equation. In the simplest form, only market concentration (measured by the HHI[25]), unbundled local loops as a share of total copper loops and the ICI are included as independent variables. The LLU coefficient is negative and significant, suggesting that unbundling has a negative effect on investment, as other literature has found.

However, in their most complete version of the model (model 4), which includes various interactions between HHI and LLU along with other exogenous variables, a different picture emerges. They find that the relationship between service based competition and fibre penetration is non-linear. In markets with a low or high HHI, the predicted effect of competition on fibre is clearly negative. However, where there is an intermediate degree of competition, more service based competition may have a modest impact on fibre penetration. Their finding suggests that there is an optimum level of competition: too much reduces the ability to invest and too little reduces the incentive to invest. There is, therefore, an optimal level of competition that leaves firms with the incentive and the ability to invest.

[25] Herfindahl-Hirschmann Index. A measure of market concentration calculated by the sum of the squares of the each firm. The closer the HHI is 10,000 (100^2), the more concentrated, or less competitive, the market.

Figure 23: Relationship between Competition and Investment, in Fourie and de Bijl (2018)



4 Risk and Cost of Capital

All projects are subject to some degree of risk: costs may be unknown, especially when a new technology is used, and the level of demand may also be unknown. This section of the Literature Review examines the literature concerning four ways in which risk by be mitigated through regulatory action: commitment, co-investment, Real Options and vertical separation.

4.1 Regulatory Commitment

In a highly regulated sector, such as electronic communications, there may also be a degree of regulatory risk if the investing party considers that the regulator may expropriate its profits (Gilbert and Newbery 1988, 1994). The European Commission recognises the need for regulatory certainty through the Code. For example, Recital 188 states:

> *"National regulatory authorities should, when imposing obligations for access to new and enhanced infrastructures, ensure that access conditions reflect the circumstances underlying the investment decision, considering, inter alia, the roll-out costs, the expected rate of take up of the new products and services and the expected retail price levels. Moreover, in order to provide planning certainty to investors, national regulatory authorities should be able to set, if applicable, terms and conditions for access which are consistent over appropriate review periods."*

A seminal article on this subject (Levy and Spiller, 1994) employs transaction cost economics to highlight how political institutions interact with regulatory processes and economic conditions to exacerbate or ameliorate the potential for regulatory risk and, hence, the economic performance of the sector.

Levy and Spiller use case studies of regulation in five countries[26] and conclude that three complementary mechanisms need to be in place to prevent arbitrary *administrative action:*

> *(a) substantive restraints on the discretion of the regulator,*
> *(b) formal or informal constraints on changing the regulatory system, and*
> *® institutions that enforce the above formal —substantive or procedural— constraints.* (p. 202)

Henisz and Zelner (2001) examine the same question econometrically. Although their study examines basic, rather than advanced telecommunications services, their conclusion is still relevant:

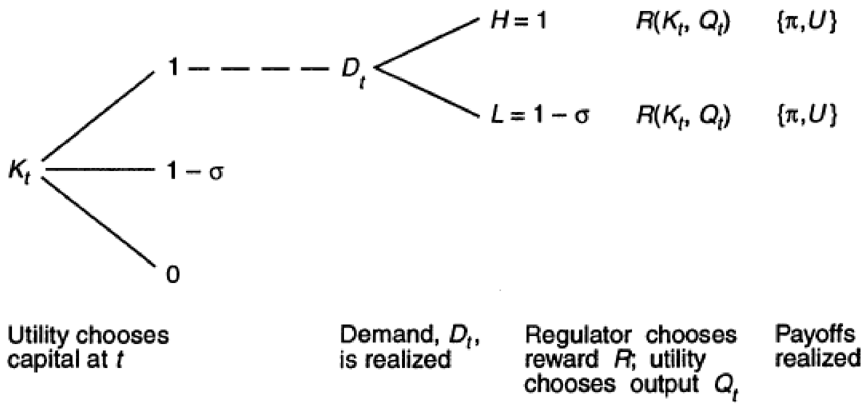
[26] Argentina, Chile, Jamaica, Philippines and the UK.

> *"Prospective investors in the telecommunications sector must realize that a low penetration level relative to the level of economic development in a country may not signify untapped market potential, but rather a large risk of expropriation by the state."* (p. 124)

A well-known, game theoretic approach to assessing the effect of regulatory risk is set out by Gilbert and Newbery (1988, 1994). In this game the utility (Gilbert & Newbery's game was not restricted to electronic communications but to regulated utilities generally) chooses whether to invest capital in a project. Once the investment is made and the facility built, demand is then realised. The regulator then decides whether to reward the utility by allowing it to retain profits or whether to expropriate the utility's profits. Finally the utility company decides output and payoffs are realised. The sequence of the game is illustrated in Figure 24 below.

As with most games, it is "played" backwards. The utility first considers what the probability of the regulator imposing regulations that expropriate its profits, and therefore whether the original investment will be profitable. If the utility considers the risk to be high then it is likely not to make the investment but maintain the current technology.

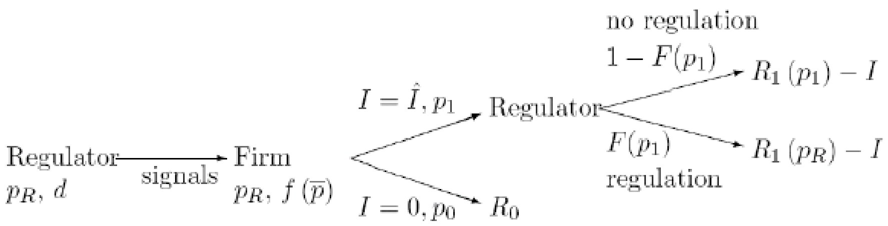
Figure 24: Basic Regulation Game



(Gilbert and Newbery 1994)

Blum, Growitsch and Krap (2007) considers Deutsche Telekom's decision to invest in a fibre network but only to do so if the regulator agreed not to regulate it with regard to access and pricing (in other words to allow a regulatory holiday) and apply a similar game theoretic model shown below in Figure 25.

Figure 25: Decision tree of the game theoretical decision model



(Blum et al, 2007)

In the first stage, the regulatory authority signals its perception of the cost-covering price (denoted p_R) and about the extent to which it will allow the firm pricing freedom (referred to as “tolerance” (denoted ^{d}). Both can be interpreted as a “probability of intervention function” ($F(p_1)$) depending on the firm’s price. The regulator’s true tolerance limit, called the intervention price ($p_R+{}^{d}$), can be concealed to the firm, exposing the investor to regulatory risk.

The firm then decides to invest ($I=\hat{I}$) or not ($I=0$) depending on its expectation of the intervention price: whether it is set at a level that would allow it to be profitable or not. If the firm chooses to invest, the regulator then decides whether the firm’s price requires intervention or not.

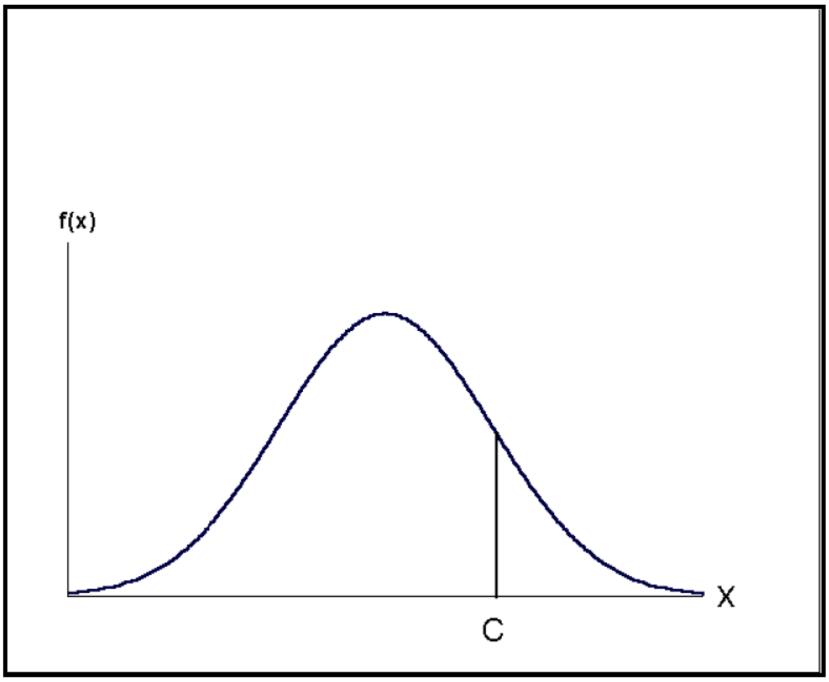
As with Gilbert and Newbury, if the firm expects that the regulator will restrict the profit it can earn, then it will not invest or, more likely, it will require a higher hurdle rate to compensate for the risk. Neither of which is a socially desirable outcome, but is a risk due to the regulator’s lack of information.

Both models are similar in concept to Hausman’s (1999) model of regulation of a telecoms network. In this model, the regulated firm’s likely profits from an investment are normally distributed. Price regulation, however, may eliminate the right hand tail of the distribution curve, thereby reducing the mean of the expected return on the new investment, as illustrated in Figure 26 below. Hausman points out that “*as the returns to the innovation become more uncertain, the expected return and the incentives to innovate also decrease*” (p. 199).

What is also important in Hausman’s analysis is that the left hand tail of the distribution curve is not affected, resulting in the regulated firm retaining all the downside risk but having its upside reward truncated.

Such regulatory risk feeds through into the NPV equation via an increase in the interest raI(*r*), which represents the cost of capital, i.e. the returns expected by equity and bond holders (Buckland and Fraser 2001, Panteghini and Scarpa 2003).

Figure 26: Elimination of Upside Reward



Hausman (1999)

Where cost recovery is not guaranteed, Charles River Associates (2012) suggests that an expected return above the weighted average cost of capital (WACC) may be required to induce investment. Similar to Hausman, they say that:

> *"… a cost-oriented access price introduces an asymmetry between the access provider and the access seeker: the infrastructure owner bears the large part of the downside risk, whereas the benefits of investment are shared with the access seekers in the case of a favourable outcome. This may distort investment incentives and therefore may require higher access prices in the case of a favourable outcome." (*p. 45)

One way in which policy makers have sought to overcome the risks outlined above is by allowing regulated firms some pricing freedom provided that they do not distort competition.

One such approach is setting prices under an Economic Replicability Tests (ERT) that allows the vertically integrated owner of bottleneck assets, such as an access network, some pricing freedom when setting the price for the asset, provided that an equally or reasonably efficient competitor[27] can compete with it in downstream markets. This requires that that the bottleneck owner sets its retail price at a level no lower than its wholesale access charge plus efficient downstream costs. This allows the bottleneck owner to earn a reasonable return on its network investment without excluding downstream rivals from the market.

Charles River Associates adds the caveat that departure from cost based pricing may lead to higher prices for consumers and should be only used when trying to induce investments.

Ofcom (2018) seeks to address the question of regulatory certainty for both consumers and investors through what it call the "fair bet" principle. It describes this as:

> *"In practice, this means that we hold off from regulating the prices of new risky investments until the investments have proved to be successful. Even then, we would only regulate prices if Openreach had market power and any regulated prices would give Openreach the ability to earn returns above its normal cost of capital." (*p. 26)

Ofcom considers that the fair bet principle gives certainty to investors but that it could be possible to give them even more certainty, for example by reaching a conclusion on the appropriate cost of capital to be used when undertaking any future fair bet assessment. Alternatively, it could seek to identify the level of up front risk faced by Openreach and therefore to pre-specify the period over which Openreach will have pricing flexibility.

Whilst not explicitly stated by Ofcom, the fair bet principle is a response to the issue raised by Hausman. It allows the regulated firm, in this instance Openreach, to enjoy the upside reward as well as face the downside risk.

4.2 Co-Investment

The Code promotes the idea of co-investment as a means of reducing uncertainty and therefore the cost of capital. It states:

[27] A Reasonably Efficient Competitor (REC) approach can be used in regulated markets where the aim is promote rather than protect competition (see European Commission (2010) '*Commission Recommendation of 20th September 2010 on regulated access to Next Generation Access Networks'* SEC (2010) 1037) and European Commission (2013) '*Recommendation 2013/466/EU on non-discrimination and costing methodologies'*. BEREC has found that 12 of the 21 NRAs that use an ERT employ the REC standard (see BEREC (2014) 'Guidance on the regulatory accounting approach to the economic replicability test (i.e. ex-ante/sector specific margin squeeze tests)' pp.60-61.)

> *"Due to current uncertainty regarding the rate of materialization of demand for very high capacity broadband services as well as general economies of scale and density, co-investment agreements offer significant benefits in terms of pooling of costs and risks, enabling smaller-scale undertakings to invest on economically rational terms and thus promoting sustainable, long-term competition, including in areas where infrastructure-based competition might not be efficient."* (Recital 198)

Cadman (2019) is sceptical about co-investment, pointing out that whilst operators may share risks, they would also share rewards and so co-investment is likely to be most relevant for capital constrained operators. Abrardi and Cambini (2019) report on a number of papers that address this question (including Nitsche and Wiethaus 2011, and Inderst and Peitz 2012), but find that "*apart from a series of theoretical papers and a single laboratory experiment, very few empirical evidences exist on the impact of co-investment agreements on ultra-fast broadband deployment*" (p. 196).

Vogelsang (2019) says that there are two outcomes in the literature on co-investment: first that it leads to more infrastructure competition than under access regulation and secondly that it may lead to collusion and so needs policing by competition authorities. He points out that the Code provides for free entry by additional partners in a co-investment, but that this will only occur if information accumulated after the original investment is positive. In addition, he suggests that the regulatory discretion allowed under Art. 74 of the Code, increases regulatory risk.

All his concerns notwithstanding, Vogelsang concludes:

> *"If (…) collusion [amongst co-investment partners] does not occur co-investment projects should be particularly competitive because the forward-looking costs relevant for pricing decisions are close to zero. This contrasts with wholesale access-based pricing, where the access charges are the opportunity costs relevant for pricing"* (Vogelsang 2019, p. 4)

We can interpret Vogelsang as meaning that co-investment partners who have built their own networks face a predominantly fixed cost with minimal variable costs. The marginal cost of an additional unit of output is therefore close to zero. By contrast, a purchaser of wholesale access buys units of output from a provider and so faces a real cost, which would then be passed on to consumers.

Aimene, Lebourges and Liang (2019)[28] empirically explore the impact of co-investment in France on broadband adoption, coverage and competition. They use a dataset from 2015 –

[28] The authors are all employees of Orange but state the opinions in the paper are their own and not those of Orange.

2018 covering the Zones Moins Dense (ZMD) as the part of France where the regulator (Arcep) imposes specific forms of co-investment obligations on operators that build FTTH infrastructure. They explain that an operator intending to roll out an FTTH network in a ZMD is obliged to inform other operators and allow them to share in the cost of investment, in return for long term rights to the newly deployed FTTH network.

Their econometric model first examines whether coverage is affected by co-investment. Once they correct for selection bias (i.e. selection of municipalities on exogenous economic factors), they find co-investment has no significant effect on FTTH coverage[29]. In other words, their model suggests that there are no more municipalities that have FTTH as a result of co-investment than would have had them anyway, once selection bias is accounted for.

However, they do find that where co-investment takes place, there is a significantly higher rate of adoption by consumers. They find that in municipalities with co-investment adoption is 7.6% higher (significant at 99%) than where it has not taken place. They also find that competition is higher, with Orange losing 7.8% market share where there is co-investment, although it is not clear which operators are gaining from Orange's loss.

Aimene, Lebourges and Liang (2019) is so far the only empirical study of the effects of co-investment. Until further such studies are conducted we cannot be certain that co-investment either promotes or constrains investment in VHCNs.

4.3 Real Options

Investments are rarely "now or never" and so the timing on when to make the investment matters. The investor can exercise an option to wait before investing at all, or may opt to limit investment now with the option of making follow-on investments if the initial project is successful. Charles River Associates (CRA) (2012) describes the choice facing investors:

> *"In a world of uncertainty, the relevant comparison for a potential investor, in general terms, is not between the NPV of investing today and the NPV of never investing (or between the NPV of investing today and zero) – rather, it is between investing today and waiting (and then perhaps investing at some point in the future)."* (p. 39) (emphasis in original)

This choice over when to invest is referred to in investment theory as a "Real Option". It is referred to as "Real" because it typically references projects involving a tangible asset instead of a financial instrument.

[29] This finding is in contrast to an earlier working version of their paper that did not correct for selection bias.

The question of Real Options in telecoms regulation was first considered by Pindyck (2007) in the context of regulated access to unbundled network elements (UNE) under a Total Element Long Run Incremental Costs (TELRIC) regulatory regime. However, the paper has some lessons for VHCN investment. Pindyck argues that the NPV equation needs to be modified when an investor has Real Options. This is because the NPV compares investing today with never investing whereas the "correct comparison" would be between investing now and waiting and perhaps investing at some specified time in the future. Although it should be borne in mind that an NPV decision compares the prospective investment with the next best use of capital.

He uses an example of an Incumbent Local Exchange Carrier (ILEC) deciding to invest in a switch where demand is known for the first two years and unknown for years three and four. In the later years demand will either grow by the same amount as years one and two, or fall back to the base level before the investment was made with equal probability. In calculating the NPV, Pindyck assumes that the ILEC must make the investment for all four years, even though it knows demand in years three and four is uncertain, and will face no competition. Pindyck sets the values in the NPV equation such that the NPV equals zero.

He then recalculates the NPV on the basis that there is uncertainty in years three and four and to meet this uncertainty the ILEC buys two two-year switches in years one and three, rather than a four year switch in year one. The ILEC only buys the second switch if the expected demand materialises in year three. This results in an NPV substantially greater than zero and equates to the option value that is lost to the ILEC by being required to commit to the market for four years.

Pindyck then introduces competition. In this version, the ILEC is required to invest for four years, but the Competitive Local Exchange Carrier (CLEC) does not enter until year three, and then only if the demand materialises. The option value is thus transferred from the incumbent to the entrant. The incumbent generates a negative NPV and the entrant a positive NPV of the same value.

To correct for this, the ILEC is allowed to adjust its price to one that generates an NPV of zero and "with this correction, the regulatory regime now comes closer to simulating a competitive market, which is presumably the goal of the regulations in the first place" (Pindyck 2007, p. 292).

IRG/ERG (2007) discuss the relevance of option theory in a regulated context. They suggest that if there is value to be gained by an investor waiting until more information is available, this would be reflected in a lower cost of capital through a lower risk premium. They also suggest that calculating the value of real options is difficult in practice and that best practice has not yet been determined.

Charles River Associates (2012) points out that if the regulator sets the access price to yield an NPV of zero, this could distort the investment decision because it does not take account of uncertainty.

Where a regulated firm is not able to realise the value of Real Options, through delaying all or some of the investment until demand and cost conditions become clear, and where the firms faces competition, there is a strong disincentive to invest. As Pindyck shows, the NPV of the investment may be substantially negative. Allowing the firm to realise the value of Real Options may therefore be a determinant of investment.

A further potential weakness of Real Options theory in the context of NGA networks, but one not mentioned in the literature, is the length of time it takes to plan and build a network, which may mean that the investor has to commit to making an investment early and so not be able to realise the option value of waiting.

4.4 Structural Separation and the Wholesale Only Model

There is a growing interest in structurally separating the access network, where it is seen as an economic bottleneck, from the retail service provision parts of telecoms companies, as a means for promoting network investment and competition in downstream markets. In parallel, there is a growing interest in independent wholesale only businesses providing networks to retail service providers, perhaps in competition to the incumbent operator.

The question of vertical separation of incumbent operators first arose with Ofcom's proposal for the functional separation of BT in 2005. The pros and cons of separation were subject to much debate (Cadman 2010, Tropina, Whalley and Curwen 2010).

Avenali, Metteucci and Reverberi (AMR) (2014) model the effects of vertical integration, functional and ownership separation on broadband investment and welfare[30]. Their model includes an upstream firm that provides access to the bottleneck to two firms (the incumbent and the entrant) that compete in the downstream retail market under the three industry structures: integration, functional separation and structural separation.

Their model, although not tested empirically, generates a number of interesting propositions. First, they find that "*no single vertical structure brings about the highest investment independent of the level of the access charge*" (p. 75). Next they find a "clear cut" result that the access charge is always higher under ownership separation than under

[30] Functional separation refers to the creation of a separate business unit within the vertically integrated firm that operates under strict rules to prevent from favouring its own downstream business. Structural separation refers to separation of ownership, i.e. the upstream and downstream businesses are independent of each other.

functional separation. Vertical separation also increases consumer surplus as long as it effectively improves downstream firms' ability to offer value-added services. Finally, functional separation often yields the highest welfare, although it never yields the highest level of NGA investment.

Sidak and Vassallo (2015) examine the short and long run effects of the functional separation of BT (via the creation of Openreach) over the ten years since it came into force. They find a number of short run benefits, in particular low prices. However, they also find that investment and quality had declined. They conclude:

> *"On balance, although functional separation has offered short-run benefits to U.K. consumers in the form of lower prices, investment in next-generation networks is lagging compared with the rest of the world. This result is consistent with our empirical finding of lower than predicted broadband demand. Whether the functional separation of Openreach from BT has been a success or a failure depends on whether one values long-run consumer welfare more or less than short-run consumer welfare."*

Cadman (2019) also questions whether the legal separation of Openreach as a separate company within BT Group will necessarily lead to increased investment, pointing out that the fundamental conditions of demand and costs do not change because a previously integrated firm becomes subject to separation.

Similar to the vertical separation model is the recent development of new entrants building alternative networks on a "wholesale only" model, i.e. entrants choosing not to take part in retail activities and only provide access to service providers. This is a new commercial phenomenon, although there have been initiatives in the public sector (Gillett, Lehr and Osorio 2004).

Barclays (2018) suggests that until recently such a strategy for commercial players was almost unthinkable. However, today there are substantial opportunities, in particular in Italy, Germany and the UK. Barclays regard slow progress by the incumbent operator in building out their FTTH networks as a key opportunity for independent wholesale only operators. They also see having the right partners and a fertile retail market as other key ingredients. Barclays assess the risk for several European incumbent operators in Figure 27.

Barclays suggest that BT and Deutsche Telekom have "struggled" to make a business case for FTTH largely because they assess the opportunity against the copper revenue annuity in a way that new wholesale only operators do not have to. What Barclays also pick up is that there need to be retailers who are happy to switch to a wholesale only operator. It is unlikely that the incumbent's retail arm will do so, so independent service providers must have the capability and willingness to switch network provider.

Figure 27: Assessing Wholesale-Only Opportunity

	Cable infrastructure	FTTH Fibre	Disruptive stakeholders	Retail support	Risk (to incumbent)
Italy	None	Low	Enel	High	High
UK	Medium	Low		High	High
Germany	High	Low	Local carriers	Medium	High
Switzerland	Medium	High	Utilities	Low	Medium
France	Medium	Medium		Low	Low
Spain	Medium	High		Low	Low
Netherlands	High	Medium		Low	Low
Belgium	High	Low		Low	Low
Portugal	Medium	High		Low	Low

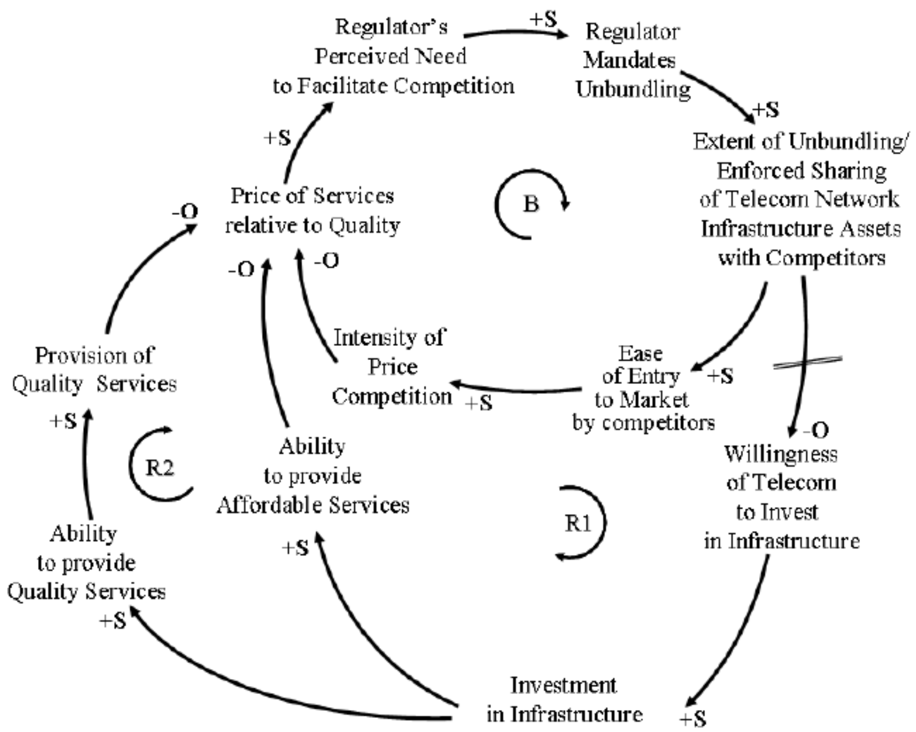
(Barclays, 2018)

5 System Dynamics Models for Telecoms

In this section of the literature review we review the literature that has used System Dynamics (SD) models in the telecommunications sector. Even though these are not necessarily related to investment determinants, these papers help us understand how SD can be used in the telecommunications sector.

Davies, Howell and Mabin (DHM) (2008) compares two systems-views modelling techniques applied to the decision to unbundle local loops in New Zealand: SD and Theory of Constraints (TOC). SD is based on Causal Loop Diagrams (CLDs) that map the relationship between actions and outcomes and incorporates reinforcing and balancing loops – feedback mechanisms that either create vicious/virtuous circles or set some limit on an outcome. This is illustrated below as Figure 28 taken from DHM.

Figure 28: Illustrative CLD for the telecom unbundling case

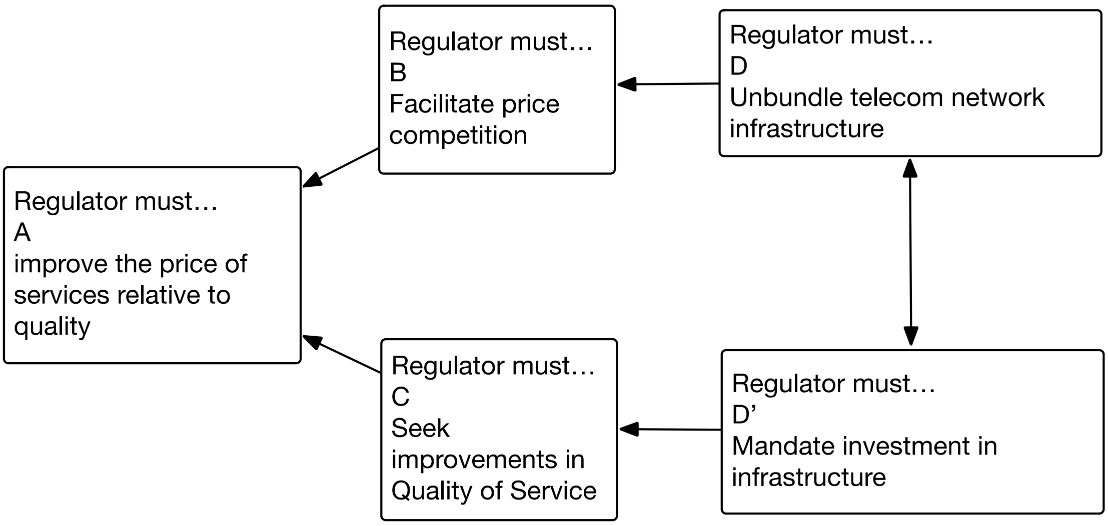


Davies, Howell & Mabin (2008)

Each action at the tail of an arrow may result in more of the outcome at the head of the arrow (depicted +S) or less of it (-O). For example, the lower right quadrant suggests that the more Telecom New Zealand[31] is willing to invest in infrastructure, the more investment in infrastructure there will be.

The alternative model examined by the authors is the TOC "Evaporating Cloud" (EC). This is a conflict resolution methodology that seeks to assist organisations make choices between mutually exclusive options. For the situation DHM explore, this is whether or not to mandate unbundling, given the overall objective of improving the price of services relative to quality. This is illustrated below as Figure 29.

Figure 29: TOC Evaporating Cloud for the Telecoms Unbundling Case



The dilemma in [Figure 27] would be read as follows:
…that in order to ensure objective A the improvement of price and services relative to quality, the Regulator must B facilitate price competition…
…and in order to B facilitate price competition, the Regulator must D intervene to ensure the enforced unbundling or sharing of Telecom's asset infrastructure.
On the other hand, another view is:
…that in order to ensure objective A the improvement of price and services relative to quality, the Regulator must also C seek improvements in the quality of services…
and, in order to C seek improvements in quality of services, the Regulator must intervene to ensure Telecom D' invests in telecommunications infrastructure.
Hence the conflict!

[31] Since this article was written Telecom New Zealand has separated into two businesses: Chorus, which owns and operates the network, and Spark, the retail service provider.

(Davies, Howell, Mabin, 2008)

The authors conclude that CLDs are better at communicating the interconnectedness and interdependence in a situation than the TOC narrative.

> *"In doing so, they can help build an understanding of the systemic nature of relationships, not only highlighting the dynamic time-based nature of feedback, the existence of balancing (B) and reinforcing (R) feedback loops, delays and side-effects; but also distinguishing between individual (say, Regulator or Telecom) and systems behavior, between seemingly predictable individual behavior and local outcomes, and the systems behavior that may be expressed as the unpredictable or unanticipated 'emergent' properties of the system.* (…) *Additionally, we may gain recognition of how such individual or system behavior can lead to unintended, unanticipated, unwanted, yet often patterned and predictable outcomes or consequences – and therefore, how alternative actions may be more appropriately evaluated.* (p. 161)

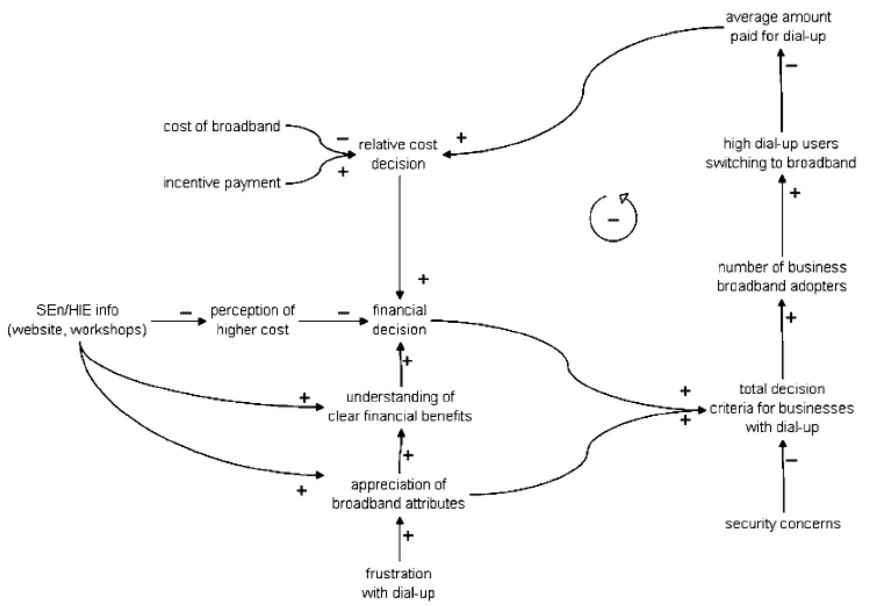
Howick and Whalley (2007) uses an SD approach to understand the drivers of broadband adoption in rural and remote areas of Scotland. At the time the article was written, 51% of Scottish households had Internet access, but only 30.6% of households had broadband access. The dial-up users were disproportionately in remote and rural areas of the country.

Howick and Whalley use CLDs to map the key factors affecting decision criteria for broadband adoption by current residential and business users of dial-up Internet access. Figure 30 below shows the key factors they identify as affecting the decision by businesses to adopt broadband.

The authors say that the decision is primarily based on the costs and benefits of broadband relative to dial-up. However, factors such as the availability of an incentive for payment and concerns about security may also have an effect on the decision.

Later in the paper, the portion of the SD model that captures influences on business is also presented followed by presentation of some results from the model. In particular, they present adoption curves for businesses and households assuming no future policy changes, which shows business adoption rate is slower than for households and that both segments reach saturation at about 80% penetration. They then simulate changing some of the policies to see which ones have the most effect on the penetration rate.

Figure 30: Key factors affecting decision criteria for businesses with dial up



(Howick and Whalley 2007)

They first show the result from changing the impact of policies to encourage an appreciation of broadband attributes. This increased the rate of adoption but not the upper limit. So the model identified a need to increase the number of households and businesses that believe that they do need broadband access. This requires understanding the needs of people who currently believe that they do not need it. Four other key policy proposals are suggested: focussed marketing campaigns, local champions, incentives and online public services. They conclude this discussion by saying that there is need to identify whether a "killer app" for broadband actually exists[32].

Casey and Töyli (2012) use an SD model to examine the impact of technology harmonisation and mobile number portability (MNP) on the diffusion of mobile phones in Finland. They develop separate conceptual models of mobile diffusion and competition. The former describes how potential users interact with current users through a word of mouth process, and then how active users interact with mobile network operators (MNOs) who expand their network to meet expected demand. The competition model shows how firms interact with each other and how end-users respond to this. This model consists of three reinforcing loops that drive a decrease in mobile prices and three balancing loops that restrict any price decrease.

[32] Recall that this article was written in 2007, the year the i-Phone was launched and five years before the launch of Netflix in the UK.

The authors construct a quantitative model using data from Finland, where, they say, the rapid diffusion of mobile can be accounted for by harmonised expansion of the GSM standard and that the Finnish regulator (FICORA) has promoted competition, with MNP as a key policy. They use this quantitative model to undertake retrospective simulations of the diffusion and usage of second generation (2G) mobile networks testing the effects of technology harmonisation and MNP.

They find that a policy of technology harmonisation rather than competition had a positive effect on diffusion, with the user base reaching near full penetration earlier under harmonisation than if the regulator enforced technology competition. The 'Direct network effect' reinforcing loop identified in the conceptual model was stronger under harmonisation, in part reflecting more affordable handsets. Users also enjoyed the network effect of being part of a worldwide base of interoperable handsets and networks.

With regard to MNP, they found that its introduction lowered entry barriers leading to a rapid increase in the number of MNOs and a stronger 'increasing demand' reinforcing loop. However, increased competition led to diminished profitability and to firms exiting the market or merging. When MNP is not introduced in the simulation, the number of MNOs remains limited.

Graham and Godfrey (2005) presents a case study of the use of SD modelling in a regulatory dispute in Hong Kong. They explain the background to the case as the Hong Kong telecoms regulator (Office of the Telecommunications Authority – OFTA) wanting to increase competition by issuing a fifth 3G competitor to use the CDMA technology. Hutchison Telecom HK was particularly concerned about this proposal as it meant that it would be required to hand back some of its 2G spectrum for the new operator.

Hutchison worked with PA Consulting Group (PA) to develop a System Dynamics model of the Hong Kong market that could be used to calibrate the effect of the additional licensee. They developed a number of CLDs showing the interrelationship between different players and actions in the market in an attempt to capture an understanding of the market system. Graham and Godfrey explain:

> *"An interlocking and complex set of markets lies between regulatory action and the downstream consequences for the public, and it is easy for different stakeholders to draw different conclusions."* (p. 3)

Once the system was described qualitatively in the CLDs, the next stage was to produce a quantitative model that could be used for simulations to determine how the market might respond to a change in the number of competitors. The PA team, together with Hutchison, developed four base cases, reflecting the four combinations of major uncertainties for the licensing issue, and then added a 5th competitor to each base case. The results are presented in Figure 31 below. As can be seen, each of the scenarios resulted in unchanged or worse outcomes when an additional competitor was licensed.

Figure 31: Public interest outcomes are generally neutral or negative, in all combinations of the major uncertainties

	Weak CDMA 2000 competitor	Strong CDMA 2000 competitor
All W-CDMA licensees stay in the market	**What happens:** The new operator is a failure, achieving around 5% market share. It puts downward pressure on prices and causes fragmentation of the applications industry, which leads to slower development of applications and slower growth in data service usage **Impact on key metrics:** • 3G penetration – unchanged • Data usage – unchanged • Data pricing – unchanged • Applications development – unchanged • Impact on market development * – unchanged	**What happens:** The market is still underdeveloped when the new entrant arrives. The new entrant takes share of over 50%, using its ability to import new applications. Others respond with increased price cuts. Fragmentation becomes a serious problem slowing down applications development. **Impact on key metrics:** • 3G penetration – unchanged • Data usage – down 10% • Data pricing – down 5% • Applications development – down 20% • Impact on market development * – delayed approx 1½
One W-CDMA licensee drops out of the market	**What happens:** The new operator is a failure, achieving around 5% market share. It puts downward pressure on prices and causes fragmentation of the applications industry, which leads to slower development of applications and slower growth in data service usage **Impact on key metrics:** • 3G penetration – unchanged • Data usage – down 5% • Data pricing – unchanged • Applications development – unchanged • Impact on market development * – delayed 1 year	**What happens:** The market is still underdeveloped when the new entrant arrives. The new entrant takes share of over 50%, using its ability to import new applications. Others respond with increased price cuts. Fragmentation becomes a serious problem slowing down applications development **Impact on key metrics:** • 3G penetration – down 5% • Data usage – down 10% • Data pricing – down 5% • Applications development – down 20% • Impact on market development * – delayed 1 year

*** Market development is measured by time taken for the market to reach 5 billion MB/year of 3G data, typically around 2013.**
Note: all percentages rounded to nearest 5%

(Graham and Godfrey, 2005)

OFTA changed its view with regard to the release of an additional licensee as a result of this process and decided that there was "no urgency" in introducing a new competitor.

Two features of the analyses stand out as critical success factors, and stand in sharp contrast to the standard argumentation approaches.

First, the analysis was even-handed. It started with qualitative modelling and diagramming that encompassed multiple (and often seemingly opposed) stakeholder views.

Secondly, the analysis was quantitative and end-to-end. Changes in regulatory decisions at one end of the system were translated by sophisticated but strictly mechanical simulation and optimization of each competitor's investment strategy into measures of the public's well-being at the other end of the system. The assumptions were explicit and validated and revalidated, and the results follow in an auditable, understandable way from the assumptions. This leads into a particularly interesting insight from this article:

> *"The insensitivity of the regulatory impact to many assumptions will not be a surprise to System Dynamics modellers. The behavioural characteristics of feedback systems are often surprisingly insensitive to most parameter changes*." (p. 9)

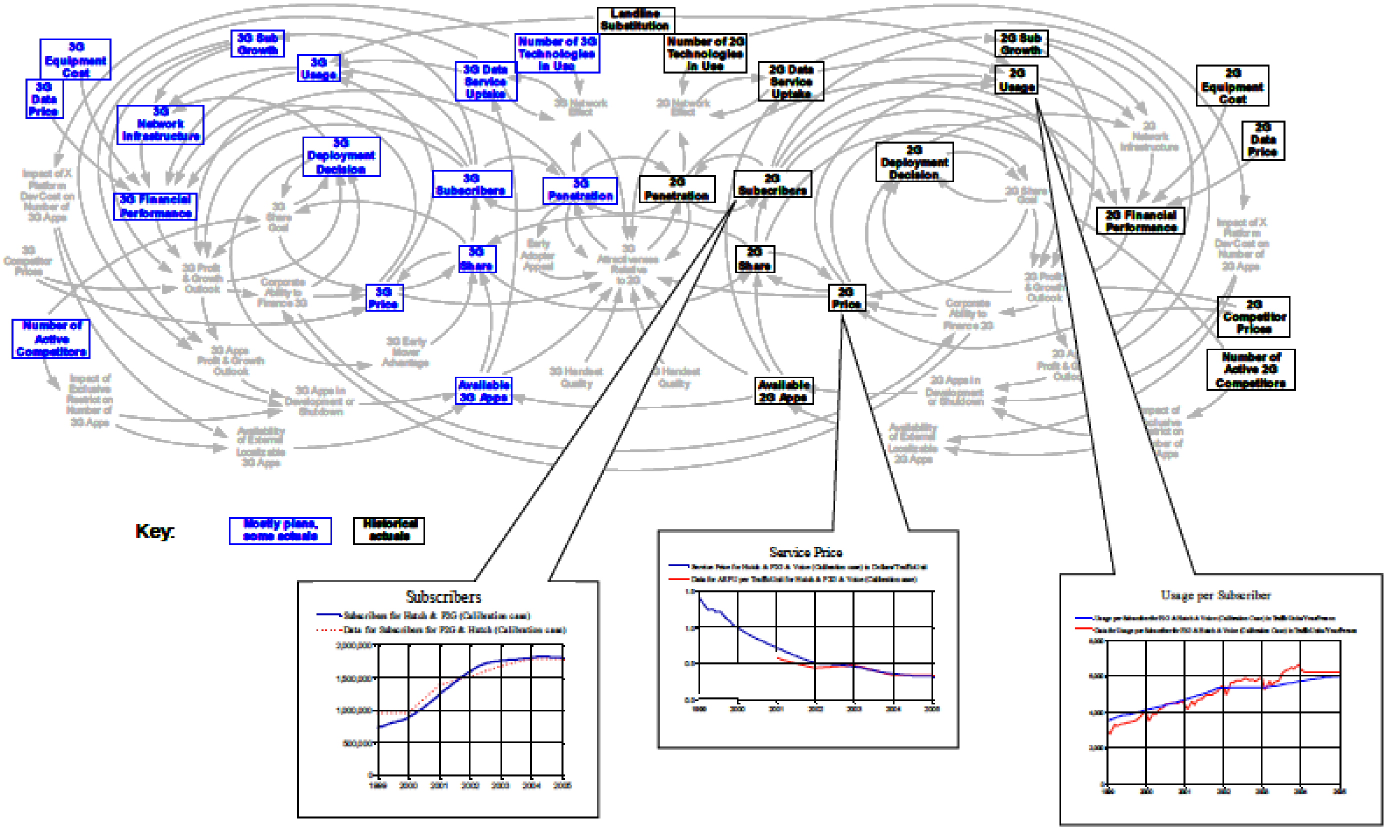
This suggests that other forms of modelling may overstate the effect of specific variables, whereas SD shows how other variables may respond to such a change or absorb the changed variable in the overall system.

Figure 32 overleaf is a representation of the influence, or causal, diagram developed for Hutchison. Its purpose is to validate (with those in a position to know) that the model considers all the relevant variables and the cause and effect relationships among them. It is important that the views and theories of all the stakeholders be represented in the model so that their importance can be impartially tested. Stakeholders may not necessarily agree about the magnitude or direction of any relationship between variables, but the model ought to capture relationships to allow them to be tested.

The graphic also illustrates how quantitative data, that is used both to validate the model (using time series data) and to examine future behaviour, relates to specific points in the influence diagram.

The purpose in presenting this model here is to illustrate the complexity and rigour of an SD model. This same degree of rigour will be used in future phases of this project.

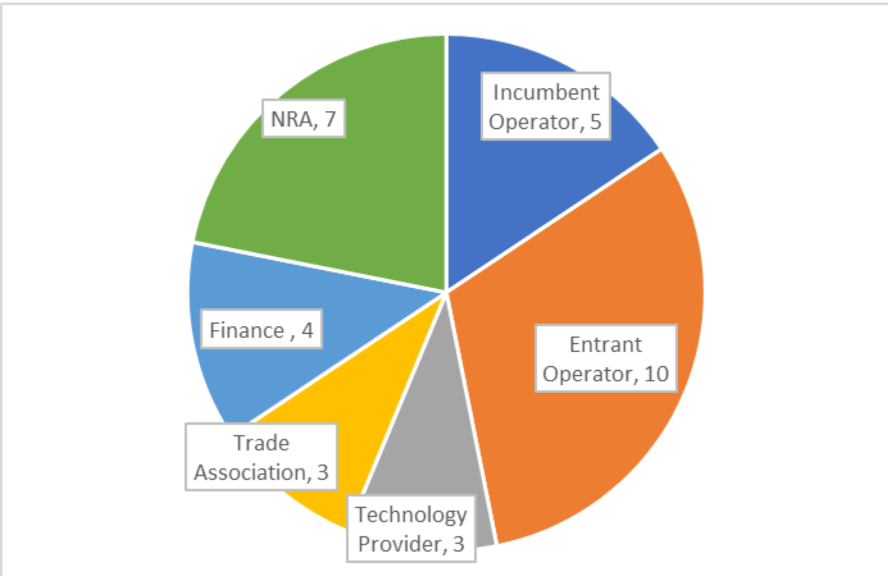
Figure 32: Hong Kong System Dynamics Model



6 Stakeholder Engagement

Research for this project has also included interviews with a number of key stakeholders, consisting of network operators, technology companies and providers of external finance. In total, we spoke with 31 organisations structured as shown in Figure 33. In general, we found a greater willingness to take part amongst entrants than amongst incumbent operators and amongst Western European operators.

Figure 33: Interview Sample Structure



The table below lists the investors, operators and representative bodies with whom one-to-one interviews were conducted by sector.

Stakeholder	Organisation	
Incumbent Operator	Deutsche Telekom Eir KPN	Orange Telefonica
Entrant Operator	Bouygues CityFibre Colt Deutsche Glasfaser	Fastweb Liberty Global Masmovil Tele2

	Eurofiber	Vodafone
Technology Provider	Ericsson Google Fibre	Google Mobile
Trade Association	ECTA ETNO	FTTH Council Europe
Finance	Cube EIB	Infracapital New Street Research

These interviews were largely qualitative but did include some questions designed to identify the regulatory and market conditions that would make one geographic area the preferred investment location. Some interviews started with the questionnaire but became unstructured as the interviewee provided a perspective on determinants of investment that did not fit within the questionnaire. In these interviews we took the decision to allow the interview to follow its own course, whilst ensuring that the points we wanted to discuss were covered.

The sample size was too small to draw statistically valid conclusions from the answers, but they do provide an indication of the conditions that are preferred for investment.

The objective of the survey was to find out what respondents considered to be the main determinants of investment. A summary of the key results is presented below in Figure 34, with further discussion following the table.

In addition to these interviews with, two workshops were held with NRAs at the BEREC offices in Brussels, which over 20 NRAs attended. One-to-one interviews were conducted with seven NRAs: ACM, Arcep, BNetzA, CNMC, DBA, PTS and RTR. The inputs from NRA interviews and workshops provided valuable input to inform the modelling process and test the development of model. These discussions did not follow the same format as the interviews with other stakeholders and so are not reported in this Section.

Figure 34: Summary of Interview Findings

	Theme	Behaviour	Source
7.1	NPV Approach	Internal and external investors take a financial approach to investment decisions.	Interviews – investors, entrants and incumbents

7.2	Capital Cost	Access to incumbent's ducts supports FTTP rollout. This was considered a key factor by some entrants although others pointed to lack of good quality ducts and difficulty in getting access to ducts in practice.	Interviews - entrants
7.3	Capital Cost	Access to other utilities' ducts also supports FTTP rollout. There was little evidence of successful use of other utilities' ducts among interviews.	Interviews – incumbents and entrants
7.4	Capital Costs	There was a reluctance to allow access to ducts by incumbents and entrants on the basis of capacity constraints. There was more willingness to rent out dark fibre.	Interviews – incumbents and entrants
7.5	Capital Cost	Simplification in planning and administration requirements supports FTTP rollout. Broadly supported by interviews.	Interviews - incumbents and entrants
7.6	Capital Cost	Regulated access to internal wiring is generally preferred – lower cost, lower admin, avoid passing buildings because landlord does not allow access. Fair price for initial installer and other users.	Interviews – finance, incumbents and entrants
7.7	Demand/ Competition	Avoid overbuild. Most entrants did not want to build where fibre networks already exist. Reduced profit opportunity.	Interviews – new entrants
7.8	Demand/ Pricing	Pricing freedom supports investment to allow investors to determine prices.	Interviews – entrants and incumbents
7.9	Capital Cost / Demand	Entrants select areas where a good relationship with municipalities can be generated. This reduces planning effort and improves adoption rates.	Interviews – entrants

6.1 NPV Approach

Both firms themselves and external investors took a financial approach to investment decisions. One external investor explained this succinctly:

> *"We look at a project and the projected NPV. If large enough we're interested. If it isn't then we're not. Simple"*

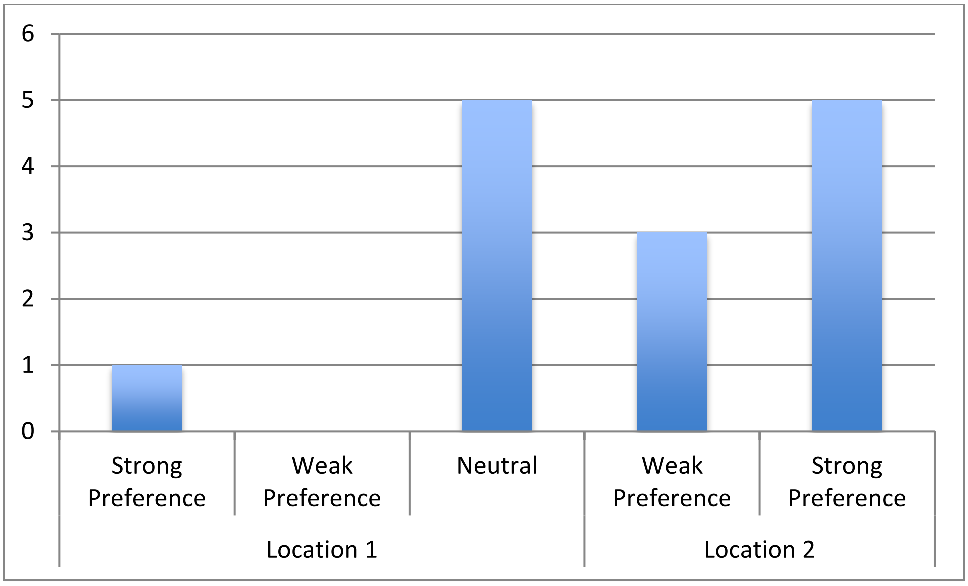
What became clear from the all the interviews was that firms and investors considered their private interests first and foremost. They needed to see that a project was likely to be profitable and generate a return to shareholders. Public policy objectives were only of interest to the extent that they might support profitability either directly, through subsidies, or indirectly through creating a positive environment. Some companies openly stated that their location decisions were based on the availability of public funds. What also became apparent was that regulatory certainty was considered important to lower the cost of capital.

6.2 Incumbent Duct Access

There was general support amongst interviewees for access to incumbents' physical infrastructure. Where this is available it was seen as having a significantly reducing initial capital costs.

As part of the questionnaire, respondents were asked to state their preference between two locations where regulatory or market conditions were different if they had a choice of investing in either location. One of these questions related to duct access. In location 1, duct access is available on a symmetric basis and in location 2 only the SMP operator is required to offer duct access. Respondents were asked to state whether they had a strong or weak preference for either location or whether they were neutral. The Reponses are shown in Figure 35. As can be seen, the answers indicate that there was a slight preference for only the SMP operator having to provide duct access, although many respondents were indifferent. Entrants suggested they would prefer to avoid areas where they may have to allow duct access as they prefer to be in control of their own resources.

Figure 35: Location Preference: Duct Access



However, there was also concern that physical infrastructure may not be in a suitable condition to provide good access and the condition of ducts, in particular, may not be known in advance. Some new entrants, therefore, did not take duct access into account when planning their networks.

It also become clear that not all countries have duct access in the final drop to the customer premises. In some countries, or areas of some countries, telephone cables were directly buried rather then placed in ducts or strung from poles. Generally, this had happened long before liberalisation of the telecommunications markets and so was not a decision of a private investor. It was therefore not possible for the entrant to obtain any duct access.

Perhaps more importantly, the incumbent could not re-use ducts in these locations to replace their copper cable with fibre to provide FTTH, which accounts for some countries having a greater reliance of FTTC by the incumbent. Such “path dependency” became a key theme of the study findings.

6.3 Other Utility Physical Infrastructure Access

We found little evidence of operators taking advantage of other physical infrastructure access in the survey. Those respondents that did mention it were generally luke-warm.

6.4 Symmetric Duct Access

Incumbents tended to support a symmetric approach to duct access: i.e. that they should have access to another operator’s ducts if available in an area. Entrants, however, tended to see symmetric access as a disincentive to investment if the incumbent could “free-ride” on their infrastructure.

Some entrants, however, saw more of an opportunity for allowing access to their dark fibre once installed.

6.5 Planning Requirements

Unsurprisingly, operators and finance companies preferred lighter regulation of planning and other administrative requirements for network build. This was seen as reducing the costs of network roll-out and so positive for investment. However, these costs were seen as more of an irritant that a deal breaker, but could have an effect at the margin.

6.6 Internal Wiring

There was no clear indication from the sample as to whether they preferred regulated access to other operator’s internal wiring or would prefer internal wiring to be unregulated. If anything, there was a slight preference for no regulation, but no firm conclusion can be drawn, given the size of the sample.

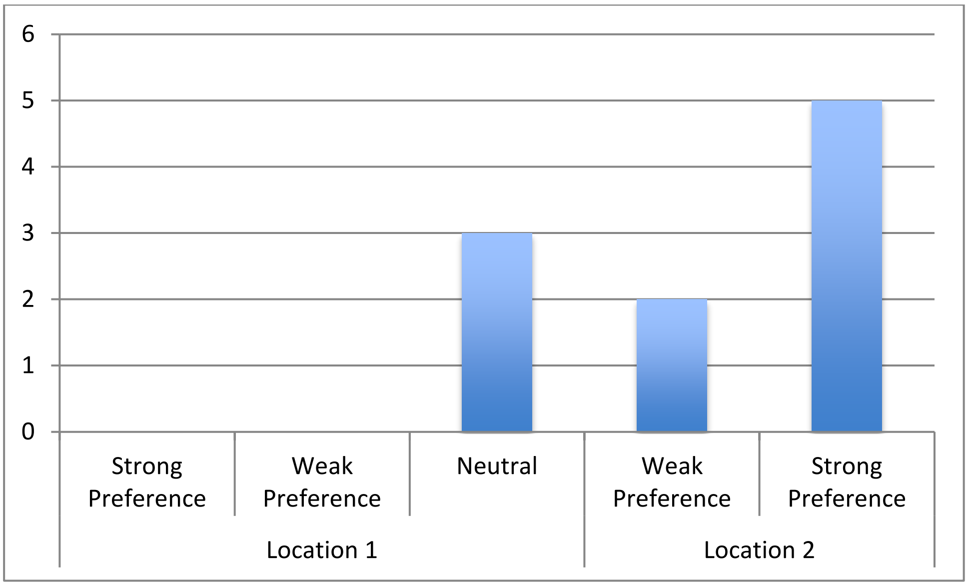
Alternative technologies for internal wiring, for example wireless micro-cells, were not seen as significant. There was substantial scepticism that these technologies would work, in particular because spectrum with a high data rate is not good at in-building penetration.

6.7 Avoid Overbuild

This was an important finding of our survey. It was summed up nicely by one alternative network builder who described their strategy as *"build where they ain't".*

Respondents were asked four questions about their location preference in the presence of actual or potential competition. First they were asked if they would prefer an area where the SMP operator had announced that it would be upgrading to FTTP (location 1) or where the SMP operator had made no such announcement (location 2). As can be seen in Figure 36, there was a clear preference for areas where the SMP operator had made no announcement about upgrading its network.

Figure 36: Location Preference: SMP Operator FTTP Plans



Similar results were obtained when respondents were asked to choose between: locations where an entrant firm was building a VHCN or where no other firm was building a VHCN; where there was a cable operator present or no cable operator was present; and where a cable operator had announced plans to upgrade to DOCSIS3.1 or had made no announcement about upgrade plans.

The clear conclusion from these answers is that network builders prefer to avoid competition if they can. Multiple networks in an area are seen as diluting the profit potential and so as something to be avoided if at all possible. One respondent explained that every operator already present reduces the potential market share for a new entrant, and therefore its revenue and profit potential. There are, however, a number of nuances to this overall position.

First, effective physical infrastructure access reduces the cost of network build and so where it is available there is less concern about overbuild. Thus, in countries such as Spain and Portugal, operators are more willing to build their own network even where other operators are present. This has a direct connection to the NPV equation, as the capital costs of building are much reduced and so less cash flow is needed to make the investment profitable.

Secondly, concern about overbuild is most present where the entrant would be competing with another FTTH network. So, where the incumbent is reliant on FTTC, perhaps because its network is directly buried, a builder of an FTTP network may still be prepared to overbuild as it considers its proposition to be superior to FTTC.

Thirdly, the combined market shares of the incumbent and a cable company, if present, in the retail market affects willingness to overbuild, especially by wholesale-only companies. Entrants with a wholesale only strategy do not see incumbents' and cable companies' retail divisions as prospective customers and so are reliant on other ISPs to be their market. If that market share is large enough they may be willing to consider overbuild against the incumbent or cable operator. However, if it is too small then they would not be willing to build. A further nuance of this point is that if the new entrant can enter the market first, i.e. before the incumbent, then it has an opportunity to provide wholesale access to the incumbent as well as rival ISPs. Thus there is a substantial first mover advantage.

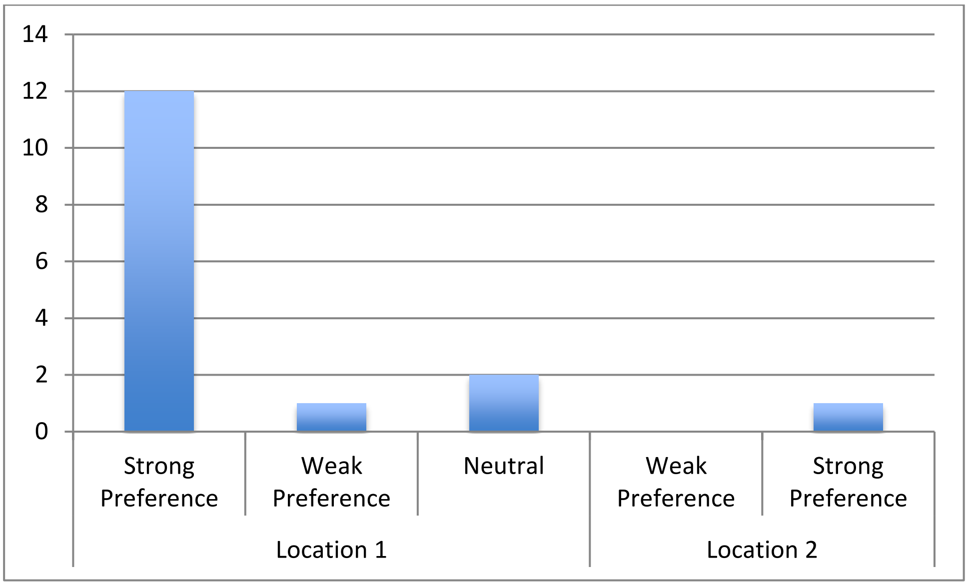
Finally, cable companies are seen by new entrants in a similar way to the incumbent telecommunications company. If the cable company has upgraded to DOCSIS 3.1, then it is seen as analogous to an incumbent that has already upgraded to FTTH. DOCSIS 3.0 or lower is seen more as analogous to FTTC and so there is more willingness to overbuild. However, entrants are very aware that the upgrade path from DOCSIS 3.0 to 3.1 is less onerous than changing FTTC to FTTP and do take this into account.

6.8 Pricing Freedom

It is perhaps unsurprising that investors see pricing freedom as a significant determinant of investment. Two pricing options were discussed: regulating prices in the furthest upstream market in which there is SMP on a cost oriented basis and then allowing pricing freedom downstream, subject to an economic replicability test (ERT); and secondly setting a regulated price for an "anchor product" and allowing pricing freedom for higher speed access. Both these forms of pricing were seen as more conducive to investment than more prescriptive regulatory practices, such as setting prices for all wholesale products where the provider has SMP.

Respondents were asked whether they would prefer to invest where only the most upstream access product is regulated with downstream pricing based on an ERT (location 1) or where prices at all regulated levels of the value chain were regulated (location 2). As can be seen in Figure 37 there was a strong preference for location 1.

Figure 37: Location Preference: ERT Based pricing



Similarly, when asked to choose between areas where anchor product pricing was used and where all access speeds were price regulated, respondents strongly preferred the location with anchor pricing.

7 Summary and Conclusions

7.1 Summary

This literature review has been developed in the light of the obligations on National Regulatory Authorities enshrined in the European Electronic Communications Code (the Code), adopted as an EU Directive in December 2018, to promote investment in VHCNs. This new Code constitutes something of an evolution from the previous Common Regulatory Framework (CRF), adopted in 2001, in that there is a greater emphasis on investment in new infrastructure, in particular VHCN.

This paper has provided a comprehensive review of the literature on the determinants of investment in Next Generation Access networks, including both FTTC and FTTH. The term "VHCN" was only introduced with the new Code and so no literature reviewed here has specifically examined the determinants of investment in VHCN *per se*. However, we have made the assumption that the same factors determine investment in VHCN as in NGA, though we recognise that the parallel is not perfect. Where feasible, we have adapted researchers' models and represented them as causal loop diagrams so that they form the beginning of the development of a qualitative System Dynamics model of these determinants.

The review of the literature is structured around the Net Present Value (NPV) model, widely used by investors and enterprises to decide whether or not to invest in a project. The review is therefore divided three sections:

- Capital investment
- Demand (as a proxy for incoming cash flows); and
- The cost of capital, including regulatory risk.

The key findings under each section are set out below

Capital Investment

Access to existing physical infrastructure designed for telecommunications reduces the capital cost of building networks and so promotes investment, with the important caveat that regulations governing access must be fit for purpose.

The literature on access to the infrastructure of other utilities is more ambiguous. There is some evidence of such access being used for telecommunications, but there is also concern that the practical difficulties of using other utilities' infrastructure make it a weak substitute.

The administration costs of building new infrastructure (for example, local planning rules) affect the overall construction cost. However, the effect has not been measured empirically, but intuitively is likely to be weak, given than these costs are small proportion of total build costs.

There may be spillover effects from investment by the first mover, which may be both positive and negative for investment in VHCN. There would be a positive effect if the first mover lowers the administration cost for later investors. However, a first mover may also reduce profit opportunities for later investors, deterring "overbuild" in an area.

Indirect or opportunity costs, arising from the cost of access to old networks, may affect investment decisions by both incumbents and entrants. The entrant's opportunity cost of investment is raised if access charges to existing networks are low. Any investment it made in new networks would have to both recover the cost of the new investment and make up for lost profits from access to the existing network. At the same time, low access prices may encourage the incumbent to invest in new networks as profits from the old network are likely to be low. By contrast, if access charges are high, the entrant's opportunity cost from investing in their own networks are low, but the incumbent's opportunity costs are high.

It is not possible to draw an overall firm conclusion from the literature that low wholesale access prices to old generation networks are good or bad for investment as the findings in the literature reviewed here are ambiguous and demonstrate a complex interaction.

Various proposals have been made to address this dilemma, such as anchor pricing and the "copper wedge", but there are no empirical studies that determine whether these proposals are effective.

Demand

There is a strong correlation across countries between the demand for broadband services and income per capita, normally measured as GDP per capita. However, the causal direction remains an open question.

Studies in the USA have found additional socio-economic drivers of demand. Education has a positive effect on demand, whilst income inequality has a negative effect.

Another socio-economic driver, discussed in European literature, is the degree to which a country has a digital way of life. The stronger the "e-culture" the higher the demand for broadband. Again, though, this is a correlation rather than cause and effect.

Demand aggregation (customers committing to taking service before the service is installed) has been found to be an effective policy to increase cash flow.

Direct subsidies, promotion of e-government and promotion of digital literacy have all been found to be positive means of increasing demand.

Competition has been found to be a driver of investment in networks. However, there are two significant arguments that may appear to contradict itself. Facilities based competition, between independent infrastructure networks (e.g. cable and FTTX) appears to increase investment as each network operator seeks to improve its product offering either to gain market share from the other or to protect its existing customer base. By contrast, it has also been argued in the literature, that where there is intense competition based on access to the incumbent's copper network (and therefore provision of ADSL services), there is a greater incentive to invest in NGA than when competition is based on VDSL. This is because the first investor in NGA can create a more significantly different product compared with ADSL than with VDSL.

Risk and Cost of Capital

The lack of regulatory certainty or predictability is a major barrier to investment. Any fear that the regulator may reduce profit potential *ex post* deters firms from making investments. Regulation must therefore allow investors to benefit from the upside of a risky investment as well as suffer the downside.

There is some scepticism about the extent to which co-investment will encourage investment. Whilst investing with partners will reduce the initial cost, it will also result in shared returns. So the net position remains the same. The one empirical study shows that co-investment has not led to an increase in coverage, but has increased competition between operators, with the incumbent losing more market share where there has been co-investment than where there hasn't been.

The decision to invest is not "now or never": firms have the option to delay until demand or supply conditions are better known. Allowing the firm to realise the value of "real options" supports investment.

7.2 Conclusions

A rational firm making the decision to invest in VHCN will only do so if the Net Present Value is positive. There are many determinants of whether this is likely to be the case and so whether a rational firm would invest. What we also see is that there is a high degree of interaction between different stakeholders, such that the decision of each stakeholder affects the actions of others.

For example, the regulator may only regulate a firm with SMP. However, how it regulates that firm affects other players in the market as well. Thus, the regulator may set a price for wholesale access to the existing network and in doing so affect both the SMP operator's and entrants' incentives to invest in NGN. The regulator may also require the SMP operator to make its physical infrastructure available to other operators in the expectation that entrants will invest in their own fibre. However, if the terms of regulated wholesale access to physical infrastructure are not fit for purpose, investment is unlikely to take place.

There is, of course, also interaction between operators directly. Where each firm decides to invest and what type of network they invest in will affect the investment decisions of others.

In some instances actions by various parties create feedback loops, strengthening the effect of each parties' decisions. Such feedback loops can accelerate the rate of investment in VHCN or reinforce a negative environment for investment. There are also natural limits to the level of investment, for example as the number of properties passed by a sustainable number of VHCNs increases, the available opportunity for further investment decreases.

Whilst the existing literature gives interesting indications of the determinants of investment in NGA and, by extension, VHCN, most research focuses on a single determinant: for example the access price to copper networks, the availability of physical infrastructure access or regulatory risk. Where econometrics is deployed, this is done within the confines of a single dependent variable and various independent variables. Very little literature looks at the system as a whole and the interaction between all the stakeholders and their decisions.

System Dynamics (SD) modelling seeks to examine decisions within that overall system. There have been some papers that use SD models in the telecommunications sector, but none that look at investment in fibre networks. It is this gap in research that is examined in this project as we seek to understand the determinants of investment using a SD approach.

The review demonstrates the emerging underlying consensus behind this change in emphasis as researchers found empirical evidence that supports one theory over another. However, there are other issues are still up for debate, where there is no consensus, and there are some areas that there is insufficient research. The table below summarises where the authors believe there is general consensus; where there is still a debate (perhaps because not enough evidence has emerged yet); and where there is too little literature to draw any conclusion.

Areas of	
Consensus	Lower cost of deployment promotes investment. Physical infrastructure access regulations must be effective to lower deployment costs.

	Open access to in-building wiring is important to prevent development a new bottleneck. Lower access prices to existing infrastructure increases the opportunity costs for entrants of building their own networks, so may deter investment. Positive correlation between access prices to legacy networks and NGN pricing promotes investment. Infrastructure competition drives investment in new networks. Static/dynamic efficiency trade off should support dynamic efficiency.
Areas of dispute	Should NRAs promote competition in or for the market? In which areas is competition sustainable at the network level and where? Or is the network a natural monopoly? Does co-investment significantly promote investment in NGA infrastructure? Does it support competitive outcomes or is there a risk of anticompetitive behaviour?
Little literature	What are the demand drivers that support investment? What role, if any, should Real Options play in regulated price setting and how should the Real Options price be calculated? What role do vertical separation/wholesale only models play in promoting investment?

Annex A. Introduction to System Dynamics

This section provides a brief introduction to System Dynamics as a primer to support an understanding of the use of Causal Loop Diagrams which are used in the literature review of drivers of broadband investment. It also provides some examples of the use System Dynamics for policy analysis as an illustration of the way that it is used to capture and understand complex and interdependent problems so that rounded policies can be devised. This provides a greater cognitive challenge than simple linear arguments and solutions, so it is hoped that the review will demonstrate the types of concepts that are considered and both the challenges and the benefits from grappling with this greater level of complexity.

A.1. The Principles of System Dynamics

System Dynamics (SD) is a technique that is used to frame, understand, and discuss complex issues and problems. It can be deployed at two levels:

I. The first level consists of a visual mapping technique to capture how people believe cause-effect relationships combine in an overall causal structure that generates system behaviour. Such qualitative diagrams, known as causal-loop diagrams or 'CLDs', can be used to explain and communicate how a system's architecture drives behaviour over time - in the context of the current study, how investment in infrastructure will grow over future years.

II. At the second level of use, elements in the CLD are quantified and causal relationships are formulated with equations to produce a working, quantitative simulation model of the system. The resulting model should mimic the observed and anticipated behaviour of the system of interest, enabling policy-makers to generate numerical analysis over time, to explore scenarios and to test alternative policies.

SD models do not conflict with theories derived from econometric studies, but rather incorporate those theories into an integrated whole – if statistical analysis finds, for example, a relationship between price (or price differential) and adoption rates for a service, then the SD model would include that relationship, and produce a quantified estimate of how profitability and investment would most likely respond to potential price changes. This is a key benefit offered by SD models. A further added value is that the same model would also show the consequences of all other causal relationships, including those that result in feedback - for example, how slower investment holds back the industry's physical capacity and constrains customer adoption of the product or service, and how this slower adoption would then further hold back the rate of investment.

System Dynamics was developed in the 1950s by Jay Forrester, initially an extension of control theory to business problems, and was formally presented as a methodology in his book *Industrial Dynamics* (Forrester, 1961). Several important texts describing the System

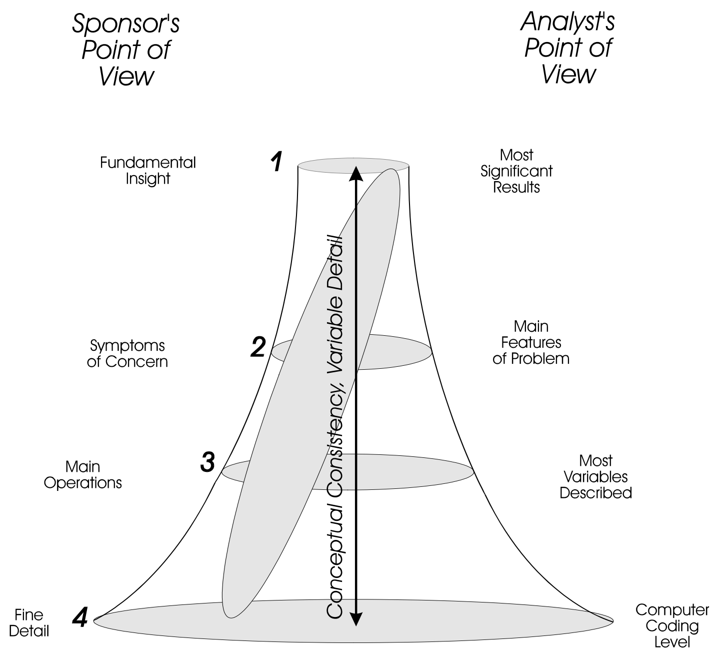
Dynamics approach have been published since Forrester's early books. For example, see Sterman (2000); Warren (2007) and Morecroft (2015).

System Dynamics encompasses the following features:

III. Dynamic Behaviour – The ability to conceptualize how systems and organizations behave over time.
IV. Cause and Effect – The ability to link cause and effect between different aspects of the system, based on theory and/or observation to determine plausible explanations for the behaviour in a system. System behaviour is described by the structure of linked sets of these cause and effect relationships.
V. The nature of the cause and effect relationships – Cause and effect influences between elements can be characterised as having a change effect that pushes the influenced element in the same direction as the causal element (indicated by a '+' or a green link arrow in a diagram) or in the opposite direction (indicated by a '–' or red link arrow in diagrams).
VI. Delays – Influences can also have an immediate impact or may be delayed by either exerting an influence after a period of time or building up over a period of time.
VII. Representing relationships in quantitative– models - In quantitative analysis the nature of the causal relationships is captured in the form of equations or functions, while exogenous elements (i.e. inputs) are captured as single values or time-series values (different values can be specified for different time periods, e.g. annually).
VIII. Closed Loop Analysis (Feedback Loops) – Chains of cause and effect relationships can often link into closed loops meaning that an element in the system can be influenced (indirectly) by changes to its own values at an earlier point in time.
IX. Reinforcing (a.k.a. Positive) Feedback – Some feedback loops can be reinforcing (or positive) leading to an accelerating impact. A simple example of a reinforcing loop is compound interest in a bank savings account, where money in the account earns interest leading to more money in the account, which then earns more interest in the next cycle. Reinforcing loops (despite often being called "positive feedback loops") are not always good, an economic crash is also an example of a reinforcing loop.
X. Balancing (a.k.a. Negative) Feedback – Some feedback loops can be balancing, tending to move an element in the system to an equilibrium point (often a goal) or a limit. A business may aim to grow customers, but a limit in the total pool of customers will be a limit on the number of customers that can be gained. As an example of a goal, most managed economies have goals for inflation rates with multiple policies aimed at achieving this goal (the difficulty in achieving these goals is an example of complex systems with multiple influences and feedback loops as well as time delays between actions and measurable outcomes often leading to over-shooting or under-shooting).

XI. Hierarchy of Levels of Analysis – It is often worth analysing system behaviours at a range of levels of detail ranging from broad high-level concepts, through a middle-level covering most of the elements of a system, to a detailed representation suitable for representing in a quantitative simulation model. This hierarchy of levels can introduce readers gradually to the concepts in the system as well as highlighting different "big picture" or "fine detail" aspects of the system behaviour. This hierarchy of levels of analysis was conceptualised by Coyle as a hierarchical cone of diagrams (1996).

Figure 38: Cone of Diagrams



(Coyle 1996)

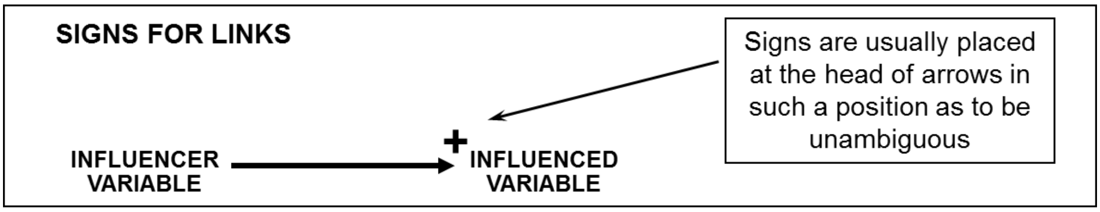
The visual mapping used by System Dynamics models tends to use one of two formats: "Causal Loop Diagrams" (CLDs) or "Stock-Flow Diagrams" (SFDs). Qualitative models are often presented using Causal Loop Diagrams although Stock-Flow Diagrams are also sometimes used for qualitative models. Quantitative simulation models nearly always use the Stock-Flow Diagram format since they more clearly define the basic building blocks that are needed for a quantitative System Dynamics model. Both formats of diagram encompass the core principles of System Dynamics but have different strengths and weaknesses in terms of communication and analysis of dynamic behaviour. In terms of Coyle's cone of diagrams, CLDs will almost always be used at the top of the cone (least detailed) while SFDs will almost always be used at the bottom of the cone (most detailed). Intermediary levels of the cone may see either CLDs or SFDs used depending on the background of the developer, the requirements of the study and/or the nature of the system being modelled.

A.2. Causal Loop Diagrams (CLDs)

Causal Loop Diagrams represent systems as a group of causal links represented as directional arrows (from Influencer to Influenced) between pairs of elements in a system. A system will consist of multiple elements and multiple causal links, with structure defined by the chained causal links and sets of links that form into feedback loops. Symbology sometimes differs between diagrams (due to modeller preferences) for the same concepts but the diagrams are subject to a common set of concepts.

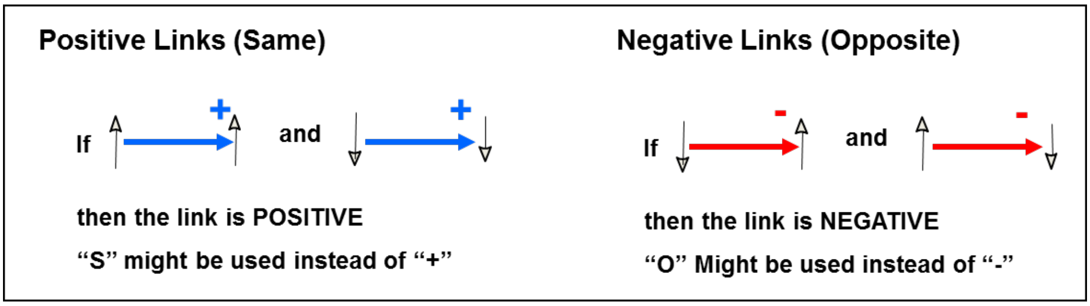
The nature of the causal links will often be represented by symbols next the arrow head indicating how a change in the Influencer (at the tail of the arrow) will affect the Influenced (at the head of the arrow).

Figure 39: A causal link showing a polity symbol indicating the nature of the relationship



A "+" or "S" (indicating Same) symbol represents a positive relationship where a change in the Influencer will tend to cause a change in the Influenced in the same direction. A "-" or "O" (indicating Opposite) symbol represents a negative relationship where a change in the Influencer will tend to cause a change in the Influenced in the opposite direction.

Figure 40: The meaning of positive or S(ame) and negative or O(pposite) causal links



Causal links might represent delayed relationships where the impact on the influenced element occurs after a delay (e.g. a delay between investing finance into telecoms infrastructure and the telecoms infrastructure being available to customers, the delay being due to time to plan and implement the building work and integration into the telecoms network). Alternatively, the strength of the relationship may build over time (e.g. customers' perceptions of the benefits of higher internet speeds). A delayed relationship is usually shown by cross-hatching or a "D" symbol on the arrow, although not all CLDs will explicitly show delay symbols.

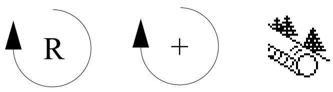
Figure 41: Symbology for causal links with delayed impacts

Sets of causal relationships can combine and cause closed loops which exhibit particular forms of behaviour that can be categorised as Reinforcing (also known as Positive) or Balancing (otherwise known as Negative) feedback loops.

Reinforcing (also known as Positive) feedback loops have an accelerating behaviour over times showing exponential growth (or decline). A simple example is compound interest in a bank account where accrued interest is added to the account balance and so leads to an increased interest payment in the next period. However, not all reinforcing feedback is good, hyper-inflation or the collapse in reputation (and profits) of a business or bank are also example of reinforcing feedback loops.

Reinforcing loops can be identified as a closed loop with no negative/opposite relationships in the loop or an even number of negative/opposite relationships. Some diagrams highlight these loops using an “R” (for Reinforcing) or a “+” inside a clockwise or anticlockwise arrow circle, while others show a snowball rolling downhill.

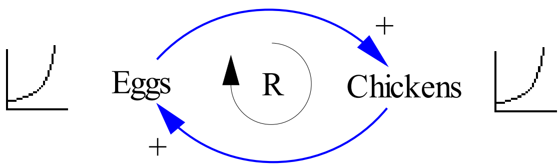
Figure 42: Common symbologies for identifying reinforcing feedback loops



Balancing (also known as Negative) feedback loops tend to have a decelerating behaviour that tends towards an equilibrium or a limit. These may be goals set by policy or management targets, or limits due to capacity constraints. For example, the speed at which fibre cable can be laid may be constrained by available skilled labour to do the work, which may create a limit to expansion of the network even if finance and demand is available. Note that other actions in the system may be targeted at shifting limits, for example training programs to increase the amount of skilled labour.

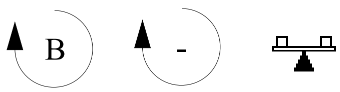
Sterman (2000) provides a simple (and slightly tongue in cheek) example of a reinforcing feedback loop involving chickens and eggs. Without any other limiting factors, more chickens will lead to more eggs being laid, and more eggs lead to more chickens. A similar, and more realistic example is the growth of a bacterial culture. A high level CLD for the chicken and egg example is shown below.

Figure 43: Simple reinforcing loop based on Sterman's Chicken and Egg example



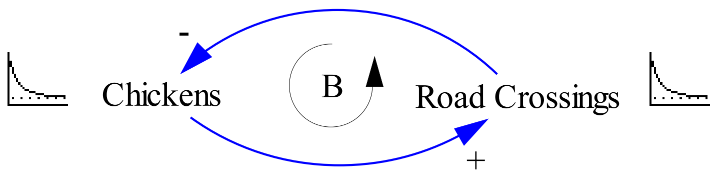
Balancing loops can be identified as a closed loop with an odd number of negative/opposite relationships. Some diagrams highlight these loops using a "B" (for Balancing) or a "-" inside a clockwise or anticlockwise arrow circle, while others show a balanced set of scales.

Figure 44: Common symbologies for identifying balancing feedback loops



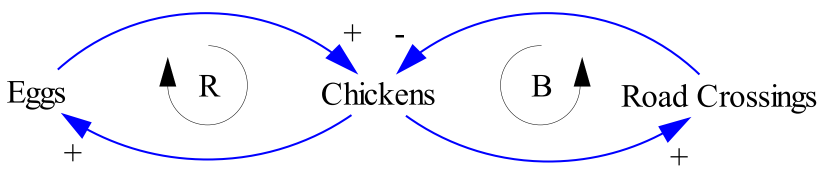
Sterman (2000) expands on the chicken and egg theme by introducing a limit on the chicken population due to them having to cross the road. In this case, chickens crossing the road may lead to their deaths and so reduce the number of chickens. The more chickens there are, the more road crossings there will be. With no other influences, this will lead to a reduction in the number of chickens to zero, but the rate of chicken deaths will decline as we have fewer chickens and therefore fewer road crossings.

Figure 45: Simple balancing loop based on Sterman's Chicken and Road Crossings example



Most CLDs will contains multiple feedback loops which will be competing or complementary with each other and producing complex dynamic behaviour. Sterman's chicken, egg and road crossings example combines to produce a system where the chicken population growth is limited by road crossings.

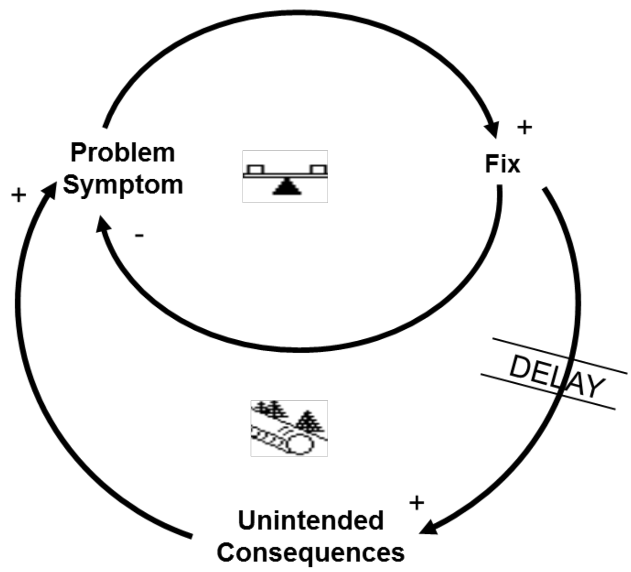
Figure 46: Combining feedback loops for Chickens, Eggs and Road Crossings



It is worth noting that the chicken, egg, road crossings example shows the use of the CLDs in a form represented by the very top of Coyle's cone of detail. It conveys concepts at a very high level in a simple format, but hides a number of important details on other factors that impact the rate of egg production, successful hatching rates, delays between egg production and hatching, and the reasons for (or at least rates of) chickens crossing the road. As described by Richardson (1986), these extra details are required to properly understand the drivers of the relative strengths of loops in CLDs. It is possible, and common, to expand Causal Loop Diagrams to include more details in order to better understand the drivers of the strengths of the feedback loops and to more explicitly show physical rates changes and information controls, but there is still a limitation in the + and – notation for understanding relative strengths of feedback loops.

Despite the limitations of high level CLDs, they have been used as the basis for developing generic archetypes that explain commonly seen dynamic behaviours. In his book "The Fifth Discipline", Senge (1990) introduced a number of high-level CLD structures, or "archetypes" describing commonly observed dynamic structures, which were subsequently expanded in a follow-on fieldbook (Senge et al., 1994). In each case the CLDs provide a map to show dynamics but are always accompanied with narratives to describe how those dynamics play out in a specific example. An example is the "Fixes that Fail" archetype where a short-term fix creates unintended long-term consequences, which require even more use of the same fix.

Figure 47: Fixes that Fail, based on Senge (with addition of polarity signs on arrows)



Senge uses the example of a manufacturing company that introduces a new high-performance part that was initially widely successful. The CEO, wishing to maximise ROI, delays introducing expensive new equipment that would make production more efficient. Production quality suffers, leading to a reputation for poor quality, leading to a reduction in sales and profits which makes the CEO even more unwilling to invest in new production equipment.

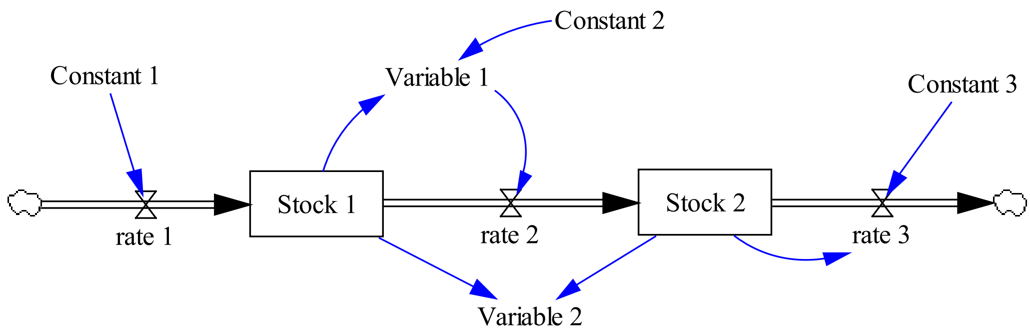
As part of the literature review, causal links (i.e. parts of CLDs) are used to capture some of the relationships expressed in the papers being reviewed. Some of these papers show closed loop behaviours that can be expressed as positive and negative feedback loops. The literature review also includes some papers that specifically use System Dynamics and CLDs to address telecommunications infrastructure studies, with examples ranging from small CLDs with a dozen causal links and a few feedback loops to large CLDs with a great many feedback loops.

A.3. Stock Flow Diagrams (SFDs)

Stock Flow Diagrams are an alternative way of representing dynamics in systems, being analogous in many ways to Causal Loop Diagrams. Many of the same concepts are present in both CLDs and SFDs but different symbology is used and flows are represented differently and more explicitly. SFDs can be used for qualitative System Dynamics models (pros and cons compared with CLDs are discussed later) and are generally the default mechanism for building quantitative System Dynamics models since they contain the structure and degree of rigour required to associate the diagrams with numerical measures and equations.

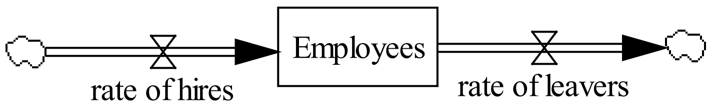
The key building blocks for SFDs are “Stocks” (also known as “Levels” or “Resources”), “Flows”, “Rates”, “Variables” (also known as “Auxiliaries”) and “Constants” (also known as “Inputs”). The figure below shows the building blocks of an SFD.

Figure 48: A Stock Flow Diagram showing all the main building blocks



Stocks represent an accumulation or a measure that characterises the state of a system at a point in time. They are often important quantities for a managed system and can represent something tangible such as “Customers”, “Employees”, “Money in Bank”, “Finished Goods” or intangibles such as “Morale”, “Brand Awareness”. A key feature of stocks is that their quantity can only be changed as a result of flows that fill (inflow) or deplete (outflow) a stock. These are shown as double-lined arrows with tap symbols. Rates define the speed at which a stock is filled through an inflow or depleted by an outflow. Rates are always expressed in terms of a quantity per time period. For example, a stock might be “Employees” measured as the number of people with an inflow rate of “hires” measured as people/month and an outflow of "leavers" also measures as people/month. In order to keep the number of Employees at a steady state the number of hires must equal the number of leavers.

Figure 49: Stock of Employees is increased by hiring and depleted by leavers

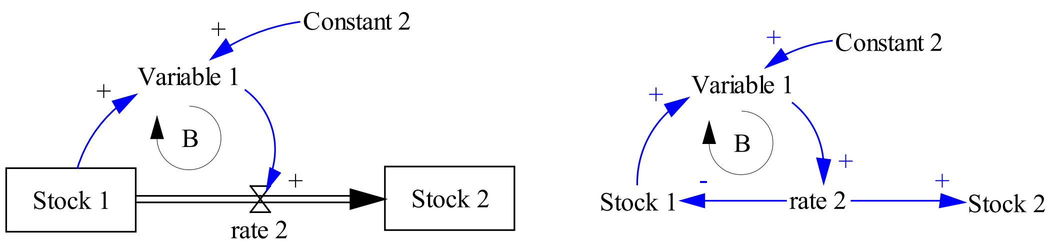


Clouds symbols represent stocks that are outside of the scope of interest and which are not measured. In the employees' example, we are not interested in the stock of people we are hiring from (although this might be of interest if there is a very limited pool of people with the appropriate skills), or the stock of ex-employees.

Variables represent a measure that can be calculated at any point in time from other elements in the diagram. These are the "effected" elements from the causal (cause and effect) links in a Stock Flow Diagram, which are shown by the single arrows. Constants only have causal links coming from them and represent exogenous fixed quantities or exogenous impacts. Despite commonly be called "Constants", these might actually change over time (e.g. a policy is changed at a particular point in time, or we might have demand for a service that is applied as an exogenous time-series), but this change is not explained by anything included inside the SFD. Causal link arrows shown in SFDs often do not have "+"/" S" or "-"/"O" polarity symbols by convention, but there is no reason why they cannot be used and may be observed in some studies. Variables that only have arrows in (i.e. no arrows out) usually represent key performance measure for the system of interest.

Like CLDs, an SFD will usually contain a number of feedback loops, but even if the SFD uses polarity symbols these feedback loops may not be so readily apparent if an outflow is included in the loop. The diagrams below show part of an SFD and the equivalent in CLD format, both incorporating a balancing feedback loop. This loop is readily apparent in the CLD but not in the SFD unless the reader is used to interpreting these in the SFD formulation.

Figure 50: Comparative SFD (left) and CLD (right) formulations with a Balancing Loop



In the SFD formulation the outflow from "Stock 1" controlled by "rate 2" is the equivalent to a CLD causal arrow from "rate 2" into "Stock 1" with a -vet (opposite) polarity (the higher rate 2, the more Stock 1 will be reduced). In the SFD the outflow must be interpreted as a

-ve polarity arrow from the rate in order to recognise the feedback loop. The CLD has the advantage of making the feedback loops more apparent while the SFD has the advantage of making the stocks and flows more explicit and apparent.

A.4. Quantitative System Dynamics Models

Quantitative System Dynamics models are simulation models that combine quantities, equations and functional relationships with the visual structure of Stock Flow Diagrams to allow numerical analysis of systems over time. The simulation model steps through time in even increments and calculates the change in stock values for each time increment.

Although simulation in general, and SD in particular, may initially seem technically complex, they merely combine known causal relationships and convert them into time-based quantified models. Each element in the model can be thought of as a spreadsheet column, with the item's name in the top cell and each period's values in the cells below. The link arrows are like cell-references. The models, provided they are properly constructed, reflect universal principles of how the real world works. Complexity comes from combining relatively simple equations with the structure of the SFD.

Calculations for each relationship in the model will take the form of mathematical equations, like those in a cell in a spreadsheet, or in terms of graphical functions relating input and output values. Inputs to the models represents exogenous variables and may be a fixed value for the duration of the time represented in the simulation, a value that varies at particular points in time (e.g. a change in policy) or a time-series that can change over the course of the simulation period.

The action of a System Dynamics simulation engine is to use the calculations in each time step to perform numerical integration to calculate the stock values, and numerical differentiation to determine rate values for a particular step in time. This simplifies the actual equations that are entered for each part of the model.

The degree of precision in the outputs of System Dynamics simulation models, like most other quantitative methods, is dependent on the degree of certainty in the relationships (equations and functions) in the model and, similarly, for any input data. Tightly bounded models based on well-known physical attributes can have very precise outputs. However, the majority of models used for assessing policy involve a broad scope for the system being studied (requiring a level of abstraction in their representation) and some degree of uncertainty in the numerical representation of the relationship and in input parameters. This uncertainty means that most models designed to test policy formulation cannot be treated as highly precise forecasting tools. By considering the appropriate level of precision of the model, they will provide an understanding of the direction of travel for key outcomes based on a mix of policy levels and potential unintended consequences. Combined with appropriate sensitivity analysis around uncertainties and assumptions, they can be used to assess the robustness of policies against uncertainties that are present in the system.

A.5. Use of Causal Loop Diagrams (CLD) vs Stock Flow Diagrams (SFD)

Causal Loop Diagrams and Stock Flow Diagrams both embody fundamental aspects of System Dynamics but demand different levels of representational rigour in their formulation and differ in the ease of identifying feedback loops and stock/flow elements. It is almost essential that the SFD formulation is used for quantitative simulation models since the explicit representation of stocks and flows is essential to the calculation process used in simulations.

SFDs require explicit representation of stocks and rates, which implies a certain degree of detail that might obscure some high-level relationships and dynamics that we wish to communicate towards the top of Coyle's cone of diagrams. In these circumstances the use of CLDs might be preferable, particularly since it is easier to identify feedback loops in CLDs than in SFDs.

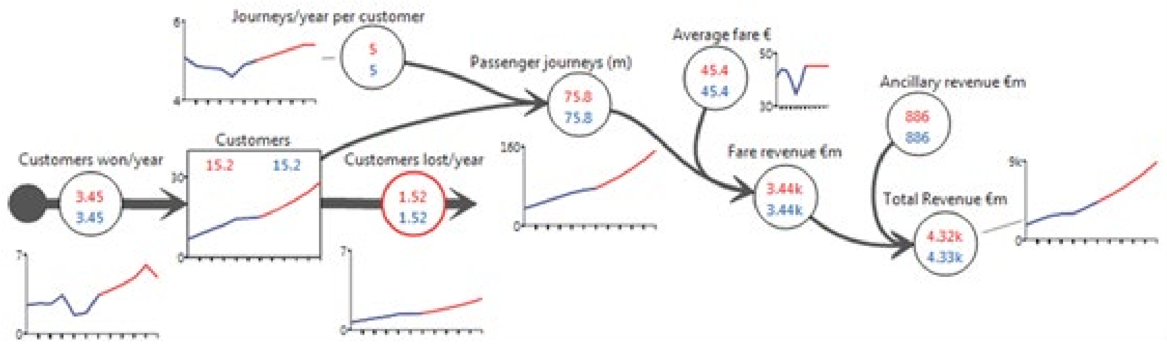
As we move into the middle area of the cone of diagrams between the very high-level representation and the quantitative simulation level of representation, the use of CLDs vs SFDs is less clear-cut and depends on the need to clearly communicate the feedback loops and the wish to communicate the important stocks (resources) and flows in the system, as well as the perspective of the system stakeholders during joint construction of the diagrams. The decision on which format to use often depends on analyst preferences for methods of knowledge elicitation and perspectives of the importance of the relative strengths and weaknesses of the diagramming approaches, and key messages to be communicated.

If feedback loop identification is the pre-dominant aim then CLDs will tend to be used, while if the emphasis is on understanding the role and development of the key resources (and the drivers on build-up and depletion of those resources) then SFDs will tend to be used. Warren (2007), for example, argues that performance outcomes of concern are driven by easily-identified 'asset-stocks' and any change in performance over time must then reflect changes to the quantities of those stocks so that gains and losses of asset-stocks are therefore the critical levers determining system performance.

It is also worth noting that there are many examples of System Dynamics diagrams that are neither pure CLS nor pure SFD but instead exhibit a mixture of the two. Casey & Töyli (2012) present System Dynamics models for mobile telecoms competition as pure high-level CLDs and then with more detail in a format that is essentially a CLD but with aspects of SFDs to highlight key stocks in the system. Ghaffarzadegan *et al.* (2011) present several small System Dynamics models for analysing public policy that are essentially SFDs in nature but make use of polarity signs on causal links and highlight the presence of feedback loops.

Warren (2002) moves qualitative SFDs further into the quantitative dimension with the Strategy Dynamics approach that emphasises numerical time-path traces by displaying time-series graphs on what is otherwise essentially a qualitative SFD. The graphs are derived from sketching numerical evidence onto stocks and rates into the SFD (along with other inputs and variable in the diagram as required) to provide evidence-based relationships beyond the standard polarity symbols. The representation then extends directly into the quantitative model realm by the addition of equations and functions to the model to calculate the numerical values, which can then be compared against the sketches for historical data and for evaluating future trends based on policy settings.

Figure 51: Part of a Strategy Dynamics model showing customer growth and revenue at Ryanair



(Warren 2008)

Annex B. System Dynamics for Policy and Investment Analysis

The following is a review of published work using System Dynamics for policy analysis and investment analysis. These represent both a mix of qualitative models using diagramming approaches and quantitative simulation models for quantitative analysis. It should be noted that this section is only a small subset of the studies that have been done using System Dynamics. The majority of studies are done as consultancy work or internal analysis by organisations that do not get published in the public domain. These examples below are an illustration of the type and scope and work that has been done, and the sorts of approaches used for the study.

B.1. Review of System Dynamics for Policy Analysis

Morecroft (2015) provides some common examples of event-oriented thinking, where a wider system view and feedback processes are not employed, as follows:

- Problem: Unruly binge drinkers; Solution: Deploy more police
- Problem: Drug related crime; Solution: Deploy more police
- Problem: Road congestion; Solution: Build more roads
- Problem: Loss of market share; Solution: Launch new product

As Morecroft points out, all of these problems have sensible sounding solutions that appear quick and decisive (a feature that we often expect and demand of our politicians). These solutions probably will work in the short term, but none address underlying problems, and will likely become increasingly expensive to implement if the underlying problem grows unabated.

System Dynamics as a methodology attempts to capture the bigger picture and capture the impacts of feedback, and so would seem to be a good fit for policy makers to better understand problems and develop more robust solutions. A common theme when reviewing papers on System Dynamics for policy analysis is that they represent a journey to explain and communicate complexity, and to attempt to persuade stakeholders that the obvious event-oriented thinking does not provide the best or enduring solution. The challenge is that the event-oriented thinking approach presents a clear linear progression with the problem on the left and the solution on the right. The System Dynamics approach on the other hand presents the situation as a series of loops which do not often have an obvious starting point. It therefore asks more from stakeholders (and readers) in terms of cognitive effort to assimilate the concepts in these models and contemplate the implications. It is hoped that the following brief review of policy focused System Dynamics studies illustrates that there is some merit to the additional effort that is required to present and understand the complexity.

Some of the most famous System Dynamics examples are of very wide-scope models of the world economy, with Meadows and the Club of Rome (1972) *Limits to Growth* being one example of published material based on this model. These broadly-scoped, conceptual models have caused considerable debate and controversy, particularly in the econometrics community regarding the validity of such wide-ranging models. However, an extensive body of work also exists involving more thoroughly validated and vetted qualitative and quantitative models for applications focussed on areas of public policy, some of which are reviewed below. Note that examples of System Dynamics models that are directly related to the telecommunications sector are presented in section 5.

Ghaffarzadegan et al. (2011) discuss in general the use of small policy models (as distinct from the large world type models). They discuss particular features of public policy such as resistance to policy change and significant opportunity for unintended consequences, multiple stakeholders, over-simplification of analysis by policy makers, and identification of endogenous system behaviour that policy makers have some control over (directly or indirectly) as well as the exogenous factors that they have no control over. The authors argue the need for small System Dynamics models, by which they mean having at most seven or eight major feedback loops. They suggest that models of this size provide important and often counter-intuitive insights into the system without sacrificing the ability to understand and communicate those insights, and are therefore the appropriate models for policy makers to help develop robust policies.

Dangerfield (1999) discusses application of System Dynamics for addressing issues in healthcare. He provides an example of qualitative System Dynamics where high-level conceptual diagramming was used to illustrate the impact of policy changes in social care of the elderly. Cuts in social funding meant that places in the community were not available for doctors wanting to discharge elderly patients from hospital, leading to bed blocking. The lack of available beds leads to longer waiting lists, with elderly patients on those waiting lists still requiring treatment in the community and so placing further pressure on social care funding on the community, creating a vicious cycle as an unintended consequence of the policy. An example of a quantitative model is an epidemiological model for AIDS which has a three stage development: an initial HIV stage with a peak in viral load (Stage 1), a relatively long asymptomatic HIV period with almost negligible viral load (Stage 2) and AIDS-Related Complex and AIDS stage (Stage 3) with high viral load and severe symptoms. These models have been used to model the development of the AIDS epidemic and evaluate the impact of prevention and treatment (in particular extending the duration of the Stage 2 period) on rates of infection and therefore the incidence of infection in the population over an extended period of time. This type of analysis allows evaluation of the areas that can have most impact on the spread of a disease and help focus research and development. In this example the dynamics of the epidemiology are well understood by stakeholders but the multiple stages and long timescales make the impacts of interventions difficult to evaluate without the use of quantitative simulation models.

Cavana & Clifford's (2006) study for the New Zealand Customs Service looked at the impact of excise policy on smoking. Qualitative CLDs were developed to identify feedback loops in the system, leading on to development of a quantitative simulation model. The purpose of the models was to examine how the level of duty charged on imported cigarettes impacts the consumption of cigarettes and the rate of smoking cessation attempts. It recognises that duties will only have an impact where they are applied, so excludes duty-free cigarettes or illegally imported cigarettes on which no duty is paid. Further, an increase in the level of duty charged will have unintended consequences in terms the rate at which cigarettes will be illegally imported, and so to be effective, increases in duty must be combined with more effort by the Customs Service to enforce customs law. New Zealand Customs Service analysts found the CLDs useful in teasing out influencing factors and affected groups and for identifying potential outcome indicators. Its highlighted complexities of the situation that required a multifaceted response and indicated some important outcome measures that were needed to properly assess the success of any interventions. However, the utility of the quantitative models was limited since the data requirements to properly set up and calibrate the model were beyond what was currently available.

Tobias et al (2010) discuss the application of quantitative System Dynamics for a wide review of policies to encourage smoking cessation in New Zealand. It was carefully calibrated to represent New Zealand smoking epidemiology and generate mortality rates that could be associated with smoking. A wide range of scenarios were run, and it was found that feasible changes in quitting behaviour could reduce smoking related mortality rates by 11% over a 35 year period. This was achieved by focusing on policies that increased quit attempts and encouraging assistance (e.g. NRT products) when attempting to quit in order to increase the success rate. The results of the study were used in the 2007 annual government budget process to provide supporting evidence for a cabinet paper proposing additional investment in cessation services in New Zealand. The government decided to invest an additional NZ$42 million in smoking cessation services over 4 years from July 2007, representing a 30% increase in the annual budget for tobacco control over this period.

Freeman *et al*. (2014) review the use of System Dynamics for public policy with a particular focus on waste management. This covers areas such as public participation in recycling, energy recovery from solid waste, as well as larger models of waste management systems, e.g. a model that evaluates the impact of policy and exogenous influences (such as GDP) on Flemish waste management. It can be seen that the higher-level conceptual models dealt with drivers on public behaviour, such as participation in recycling. More detailed quantitative models tended to be hierarchical, linking several sub-modules within the wider waste management system. On the whole these tended to focus on capacity requirements for different types of waste, and for evaluating the impact of alternative technologies for dealing with waste (such as energy recovery) on the requirements across the whole system. Freeman *et al.* noted that only one of the reviewed models was calibrated with empirical data, and that with the time-frames covered by the models, none had had the opportunity to compare model predictions with actual outcomes and refine the model. They highlighted that the models illustrate the "wickedness" (i.e. complex interdependencies) of problems and the benefits of creating learning systems. They note the importance of understanding complexity, interdependence and feedback and of understanding the intended and unintended consequences of policy interventions.

Ahmad *et al.* (2016) review the use of System Dynamics in the energy and renewables sector. The majority of the papers reviewed focused on energy policy including policies to support and encourage private investment, policies for power market deregulation, cross-border trading of electricity, and policies to promote renewable power sources and reduce dependency on fossil fuels. A common theme in most of the models is a representation of energy demand, different sources of supply, availability of finance and several economic and environmental outcome measures. The purpose of the review was to understand the nature and variety of models used in energy and renewables and evaluate the usefulness and short-comings of parts of the models. It did note how the scope of models and associated policy questions could lead to constrained solution spaces that tended to favour fossil fuels. The review also highlighted several models that identified where the structure of energy markets inadvertently encouraged fossil fuel investment over renewables even though the intention of government was to lower carbon emissions.

Ford (1999) takes a slightly different approach to the other papers for his review of electricity pricing impacts for power plant construction in the western United States. He makes use of a System Dynamics model that was originally developed for an electricity utility to help them achieve cash flow and maximise revenue rates. Relevant parts of the model were used for a high-level aggregated analysis of how pricing mechanisms might affect power plant construction cycles which in turn would affect electricity prices. Given an assumption of continued growth in electricity demand at 1.5% per year and growth in underlying natural gas prices, the fear is a cycle of under-capacity and over-capacity would develop leading to wide variations in prices over time. The supply of electricity consists of base-load plants (such as thermal and nuclear) and peak load plants (such as old coal powered and older gas-powered plants) that are only utilised at peak times when the auction price for electricity is high. As underlying demand increases the average annual electricity price rises until it reaches a point where it is economic for utilities (the model assumes these act independently) to build a new plant based on an extrapolation of future price taking into account delays to get permits and complete construction. When plants come online it creates a jump in capacity leading to lower average prices which will put off further investment until prices increase to acceptable levels. Ford then uses the model investigate impacts of changes in assumptions and on other pricing and reward mechanisms. He finds that the oscillations are sensitive to demand growth assumptions and illustrates the impacts on prices of varying demand between 0.5% and 2.5% growth per annum. He finds volatility in prices increases with assumptions on construction cost and construction duration, but volatility reduces with higher gas price growth (traced to higher efficiency in newer gas powered plants). Ford then uses the model to investigate mechanisms that could reduce price volatility, and in particular looks at capacity payment which compensate plants for having available capacity even if they are not used. This leads to higher prices in the short-term but investment in plants is undertaken more gradually and so reduces oscillations considerably. In the longer-term he determines that there would be some increase on wholesale prices to large users of electricity (e.g. smelting plants) but no retail price penalty and all prices are much more stable. The paper is an example of incremental analysis using underlying long-term data to calibrate a model but then using sensitivity analysis and policy changes to understand the behaviour of the system better. The model does not advocate the ability to accurately forecast capacity and prices but is used to investigate drivers of instability in the system and potential mitigations against that instability.

B.2. Review of System Dynamics for Infrastructure Investment Analysis

A review of System Dynamics models that have been used for the evaluation of infrastructure projects can provide some insights for the use of System Dynamics to analyse drivers of investment for VHCN. All of the examples below utilise the ability to represent a wide scope of impacts in order to undertake a cost benefit analysis of investment plans. In most cases there are decisions around scheduling of activities that impact costs and performance which will have implications on financial performance. All of the examples involve development of a quantitative System Dynamics model, but most emphasise the role of a qualitative model for communications during the design of the model and in developing a shared understanding of the system, which was often used as a mechanism for briefing wider stakeholders.

Mayo *et al.* (2001) describe a System Dynamics model built for London Underground Ltd. (LUL) to provide a common framework for analysing structural options for financing and operating the underground train system. The model was developed through interviews and causal mapping workshops with over 75 LUL staff from all parts of the business. The model includes LUL's operations (including assets, workforce and suppliers), its customers and their choices, competing transportation modes, finance, government policy and measures of operational and financial performance. These aspects are represented in a high-level CLD, and analysis included identification of competing reinforcing feedback loops for financial drivers, which could lead to increased capital investment. This, in turn, would improve the performance and capacity of the system, and lead to stronger long-term market shares and revenues. Alternatively, it may lead to short-term sweating of the existing assets, prompting service quality and revenues to be diminished.

The Mayo *et al.* paper goes on to describe the development and calibration of a quantitative System Dynamics model. The qualitative and quantitative models were used by LUL to develop and test policies ranging from relatively minor changes for borrowing to accelerate investment up to a major restructuring involving splitting London Underground into 20 private sector businesses. The outcome of the analysis was to offer parts of the transport system to different operators for investment and operation in return for performance-based payments. The System Dynamics models were then used to communicate key lessons to potential bidders and to help evaluate bids during the bidding process.

Another infrastructure study involving the London Underground is described by Curram *et al.* (2004) where System Dynamics modelling was used to support a successful bidder in London Underground's competition for the investment and operation of one of the London Underground lines. The challenge for the operator was to upgrade the line and rolling stock whilst keeping the line running, with the added complexity that the access to the underground line to undertake engineering work and do testing was extremely restricted. The purpose of the study was to relate infrastructure upgrade progress to performance metrics which in turn set revenue (including rewards or penalties).

Curram *et al.* describe how the quantitative model was developed by a cross functional team, starting with a high-level qualitative model focusing on key resources and measures of performance, and then developing a quantitative model. The quantitative was built as a series of small stand-alone quantitative prototypes to illustrate and refine particular parts of the model which were then integrated into the full model. The model included implementation of key functionality of the official contractual spreadsheet model that specified the payment and penalty scheme, so that the model could accurately capture the performance related aspects of the contract. The model provided a common basis for discussion and a repository for corporate knowledge, with the client members of the team taking ownership and being keen to talk through the model with other members of the organisation. The model highlighted the interdependence between different activities, and demonstrated that activities could not be planned in isolation but had to be done in a coordinated sequence. The model became a key tool for the newly appointed integration manager to be able to relate engineering issues to financial consequences for communication across the business functions.

Nguyen at al. (2017) describe the development of a System Dynamics model designed to expand on a Cost Benefit Analysis for the Co Chien Bridge project in Vietnam. They made use of the official cost benefit analysis report for the proposed bridge as a base for development of the model, along with group discussions with team members of the Co Chien Bridge project and other experts. The discussions led to the creation and agreement of a Causal Loop Diagram that linked the transport investment project with direct and indirect impacts on the local economy. These included direct impacts of transport cost saving and supply chain capacity improvements, and indirect impacts in terms of industrial and agricultural development, tourism, development of the labour market and falls in unemployment rates and impacts on local GDP and tax revenues. The Causal Loop diagram was developed into a quantitative simulation model based on data from the official cost benefit analysis and other rules of thumb based on wider economic and business data. The official cost benefit analysis reported an NPV of US$22 million over 30 years, an internal rate of return of 10.97 and payback time of 19.3 years. The System Dynamics model included wider indirect benefits which were discounted to Present Value and determined a payback time of 12.1 years, as well as a reduction in unemployment rate from 16.67% to 13.33%. Validation of the model consisted of testing assumptions in the data used for the model and ensuring that the output measures were internally consistent. It was highlighted that key benefits of the System Dynamics model were that structure of the model was readily visible to decision makers with key assumptions being well documented, and the results comparing the base case (no bridge) with the scenarios gives a clear picture of the breakdown of costs and benefits.

Uehara *et al.* (2018) present a model that mixes System Dynamics with an Econometric Input Output (IO) model for assessing the economic and ecological impacts of a mandated water quality restoration for the Seine estuary. Ecological damage has been caused by harbours in the area resulting in depleted sole fish stocks. Restoration costs could be applied directly to harbours, or indirectly spread across client industries. A System Dynamics model represented water quality and the impact on sole fish stocks, along with restoration strategies. Included in the model is an economic sub-system comprising of a System Dynamics implementation that interacts directly with a spreadsheet model. The authors used an industry-to-industry IO table for the Haute-Normandie region comprising of 37 sectors. This table was implemented in Microsoft Excel and comprised of three matrices: X the intermediate sales matrix, F the final demand matrix and V the value added payments matrix, and five vectors representing total industry output, its transpose, total values added payments, a row vectors of imports consumed by dustiest, and a row vector of imports consumed as final demand. The IO table is used during the simulation run to determine the economic impacts of the restoration policies across the sectors as well as adding the economic impacts of the sole fishing industry. These feed into measures of disposable income and GDP. The model uses different scenarios for the timing of restoration and allocation of costs, as well as sensitivity analysis around water quality.

The outcome of Uehara *et al*'s analysis shows the impact of policies on disposable income and GDP as well as surface water areas for nurseries and weight of sole caught. The baseline scenario of do nothing shows fish nursery areas and catches falling. The other scenarios show recovery at different rates as well as a lower rate of increase in disposable income and GDP from all restoration policies. The IO analysis also allowed impact to be evaluated for each of the sectors. The most robust policy scenario seemed to be to apply a high-level of restoration early and then tailing this off as water quality improves. This maximises benefits to the fishing industry while potentially shortening the duration of restoration and negative impact on other industries. The paper illustrates that it is possible to expand the scope of traditional IO models to include causal relationships on environmental issues. The decision on what to calculate in the System Dynamics model and what was calculated by the spreadsheet model was based on computational efficiency.

Annex C. Glossary of Acronyms

ADSL	Asynchronous Digital Subscriber Line
BEREC	Body of European Regulators of Electronic Communications
CLD	Causal Loop Diagram
CLEC	Competitive Local Exchange Carrier (USA)
CRF	Common Regulatory Framework
DCMS	Department of Culture Media and Sport (UK Government)
DSL	Digital Subscriber Line
EECC	European Electronic Communications Code
EU	European Union
FDC	Fully Distributed Costs
FTTC	Fibre to the Cabinet
FTTP	Fibre to the Premises
GDP	Gross Domestic Product
HFC	Hybrid Fibre Coax
HHI	Herfindahl-Hirschman Index (of market concentration)
ILEC	Incumbent Local Exchange Carrier (USA)
LLU	Local Loop Unbundling
LRIC	Long Run Incremental Costs
LUL	London Underground Ltd.
NGA	Next Generation Access
NGAN	Next Generation Access Network
NGN	Next Generation Network
NPV	Net Present Value
NRA	National Regulatory Authority
OECD	Organisation for Economic Co-operation and Development
OLS	Ordinary Least Squares
SD	System Dynamics
SFD	Stock Flow Diagram
TELRIC	Total Element Long Run Incremental Cost
TOC	Theory of Constraints
UFB	Ultra-Fast Broadband
VDSL	Very High Speed Digital Subscriber Line
VHCN	Very High Capacity Network
WTP	Willingness to pay

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