CRANFIELD UNIVERSITY

YERLAN DURMAGAMBETOV

“A COMPLEX SYSTEMS PERSPECTIVE ON INNOVATION, INVESTMENT AND REGULATION OF EVOLVING TELECOMMUNICATIONS NETWORKS”

SCHOOL OF MANAGEMENT
THESIS

INTERNATIONAL EXECUTIVE DOCTORATE (DBA)
Academic Year: 2013 - 2017

Supervisor: Prof Liz Varga
September 2017

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This thesis is submitted in partial fulfilment of the requirements for the degree of DBA

ABSTRACT

This thesis is a Doctoral Thesis of the International Executive Doctorate Programme (DBA) at the School of Management, Cranfield University, UK. The purpose of the study is to present the results of the research dedicated to the topic of Infrastructure Sharing, a common method to make use of the limited infrastructure resources of many stakeholders. The research aims to develop a decision support tool for a National Regulating Authority (NRA) on the basis of a software simulation representing infrastructure in use as complex systems consisting of agent and infrastructure networks. By applying a computational Agent-Based Modelling (ABM) approach to policy decisions, i.e. influence of Duct and Pole Access (DPA) to incumbent telecommunication infrastructures, the research investigates regulatory considerations that stimulate the development of alternative networks. The final deliverable of the research is a simulation tool that provides a solid foundation for simulating experiments, which allows analysis of demand for broadband services by different subgroups of users. The results of the study are of value for regulators, practitioners, representatives of telecommunication and other network industries, and scholars who deal with the topic of sustainable infrastructure development and recognise the value of a complex system perspective.

Keywords: regulation, duct access, pole access, infrastructure sharing, agent-based modelling, software simulation, facility based competition, service based competition

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LIST OF ABBREVIATIONS

ABM	Agent-Based Modelling
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
ARPU	Average Revenue Per User
BDUK	Broadband Delivery United Kingdom
BO	Board of Operators
BTOR	British Telecom / Openreach
BYOBS	“bringing your own base station”
BYOP	“bringing your own phone”
BYOPC	“bringing your own PC”
BYOPP	“bringing your own processing power”
BYOS	“bringing your own spectrum”
BYOT	“bringing your own technology”
CAPEX	Capital Expenditures
CAS	Complex Adaptive Systems
CEO	Chief Executive Officer
CIS	Commonwealth of Independent States
CPE	Customer Premises Equipment
CRA	Council of Regulating Authorities
DBA	Doctorate of Business Administration
DCR	Digital Communications Review
DEA	Data Envelopment Analysis
DM	Decision Making
DPA	Duct and Pole Access
DS	Decision Support
EMO	Evolutionary Multiobjective Optimisation
EP	Empirical Project
ESRC	Economic and Social Research Council
EU	European Union
FTTH	Fibre-To-The-Home
FTTx	Fibre-To-The-Premises
GDP	Gross Domestic Product
GR	Government Relations
GSR	Global Symposium for Regulators

IA	Impact Assessment
ICT	Information and Communication Technologies
IP	Impact Plan
IS	Infrastructure Sharing
ITRC	Infrastructure Transition Research Consortium
ITU	International Telecommunication Union
KT	Kazakhtelecom, JSC
LLU	Local Loop Unbundling
LoI	Ladder of Investments
LRT	Light Rail Transit
LTE	Long-Term Evolution
MAUT	Multi-Attribute Utility Theory
MCDM	Multi-Criteria Decision Making
MNS	Mobile Network Sharing
MVNO	Mobile Virtual Network Operator
NGN	Next Generation Network
NIS	National Innovation Systems
NISMOD	National Infrastructure System-of-Systems Model
NMN	Next Mobile Networks
NPV	Net Present Value
NRA	National Regulating Authority
NwoB	Network Without Borders
ODD	Overview, Design and Details
ODF	Optical Distribution Frame
OECD	Organisation for Economic Co-operation and Development
Ofcom	Office of Communications
OLT	Optical Line Terminal
OPEX	Operational Expenditure
PS	Positioning Study
R&D	Research and Development
RAN	Radio Access Network
RCC	Regional Commonwealth in the field of Communications
RCUK	Research Council United Kingdom
ROI	Return on Investments
SCC	State Control Committee
SJR	SCImago Journal Rank

SLR	Systematic Literature Review
SOM	School of Management
TUCP	Transforming Utilities’ Conversion Points
UN	United Nations

1 FOUNDATION

1.1 Introduction

The ignition point of this DBA research was a managerial task from the Chief Executive Officer (CEO) of Kazakhtelecom (KT) in 2012 to explore the concept of Infrastructure Sharing (IS). At the beginning of the 2010s the shift of the traditional voice telecom industry from growth to maturity stage became apparent in most markets. The market reached saturation in providing Internet access over fixed and voice over mobile connections. Growth by geographical expansion slowed down. Due to competition and regulators' pressure the Average Revenue per User (ARPU) fell drastically. On the other hand, increasing demand for digital data by converged networks and media applications provided new opportunities for industry growth but increased the problem of infrastructure shortages. Because of competition in no-growth markets, telecoms faced the problem of meeting revenue expectations under declining profitability and maintaining continuous infrastructure regeneration.

IS in telecommunications is an innovative method for many entities to make use of limited infrastructure elements, i.e. ducts, towers, networks, spectrum bands, and others. A preliminary managerial research of IS methods was conducted at KT. The managerial research on IS revealed a great deal of ambiguity and gaps in knowledge. Firstly, the term "Infrastructure Sharing" in its current formulation received massive implementation in the 2000s. Prior to that, the "Sharing" concept was used either for non-profit arrangements between parties in similar premises or in relation to development of open access and competition. The concept of IS has its roots in the scarcity of limited resources, either natural or man-made. This scarcity became visible in the 21st century as a result of huge developments of converged telecommunications and media networks.

Secondly, there is a lack of clear definition of the IS concept in telecommunications. Studies on this concept are fragmented and represent a set of separate topics, i.e. co-investment options, unbundling of fixed network elements, active and passive IS for mobile, spectrum sharing, Mobile Virtual Network Operator (MVNO), roaming, 3rd party infrastructure providers. Some topics are well researched whereas others are in their early stages. Most publications on IS are generated in business or consulting areas with academic scholars catching up with empirical research. Not all studies explicitly cite the term "Infrastructure Sharing" but clearly follow its main principle: a common use of limited resources by many entities.

Thirdly, since telecommunications are a regulated industry and recognised as part of the national economic infrastructure, the issue of regulating IS is diverse too. Certain countries prescribe mandatory sharing of selected infrastructure elements; others pursue voluntary arrangements between business entities. This lack of rules on IS constitutes a major bottleneck for promoting IS principles, as ambiguity on the regulatory side creates potential financial and litigation risks on the business side. Inconsistency among national regulators on IS was recognised by the International Telecommunication Union (ITU) which dedicated its Global Symposium for Regulators (GSR) in 2008 to the topic of IS (Foster, 2008; Lazauskaite, 2008; Lefèvre, 2008; Schorr, 2008; Webb, 2008).

Academic papers primarily focus on the scope and nature of regulatory decisions related to IS. In wireline and wireless telecommunications sharing, policies apply to network elements (local loop unbundling (LLU), duct and pole access (DPA), "bitstream" access) as well as the network as a whole (common carriage, open access, network neutrality). In analysing the mandatory versus voluntary sharing principles, the literature review discovered that various studies show controversial results on the effect of mandatory sharing. Various researchers argue that mandatory IS is not welfare enhancing (Crandall, 2005), does not enable broadband penetration (Crandall, Eisenach and Ingraham, 2013), and does not lead to an increase of competition (Hazlett, 2006) and infrastructure investment (Cave, 2014).

Academic papers agree that the pressure on tailoring balanced regulatory practices related to infrastructure development will increase as the demand for digital services and content continues to grow exponentially. The United Nations (UN) declared the Internet to be a basic human right (United Nations, 2011), which forces governments worldwide to connect their citizens to any place on the world map. Commercial deployment of modern telecommunication networks is economically viable in urban geographical types, whereas in rural and other underserved areas, subsidies and licence obligations are the main regulatory remedies to provide network coverage. All these findings provide reinforcement that regulators need to simulate, model, test and analyse the potential outcomes of various IS decisions prior to implementation.

1.2 Statement of Purpose

The ambiguity and knowledge gaps noted in the preliminary observations on IS suggest that there is a need for businesses and regulators to determine the dimensions of decision support to implement the most effective types of IS in national telecommunications. Since the perspectives of businesses and policy makers are different in nature, the proposed DBA research takes the broader perspective of a National Regulating Authority (NRA) to formulate the business problem statement:

There is a great deal of ambiguity in definition, exercising and regulating IS in telecommunications caused by heterogeneous and inconsistent business and regulatory approaches. There is a demand for a decision making approach to implement the most effective types of IS methods for a given set of a country's economic, geographic, demographic, and other variables to maximise economic, environmental, political and social outcomes.

A specific purpose of the research is to provide regulators with a decision support tool to enable NRAs to analyse the potential outcomes of regulatory initiatives related to the development of IS as a tool to promote competition in telecommunication markets. This study reports on the outcomes and findings, explains the contribution to academia and describes the limitations of the potential avenues for future research.

1.3 Research Question

The research aims to investigate the potential for innovation and investment in network competition via IS. The study is designed from the perspective of an NRA, and looks at interrelations between various stakeholders, e.g. users, incumbent and alternative operators, and how these interrelations affect the development of alternative infrastructures. The research recognises infrastructures in general and IS concepts in particular as complex systems consisting of agents and networks. By applying a computational Agent-Based Modelling (ABM) approach to policy decisions as the main research vehicle, e.g. the influence of DPA to incumbent infrastructures on the development of alternative networks, the research aims to answer the following research question:

"What regulatory considerations stimulate investments in Infrastructure Sharing?"

This is an overarching research question that can be tailored to a specific national context (developed or developing country), regulatory culture (interventionist or liberal), geographic type (urban or urban), network type (wireless or wireline), network elements (communication towers or ducts and poles), and demand characteristics (types and behaviour of users).

1.4 Stance of the Researcher

In this research, modelling the development of a Next Generation Network (NGN) infrastructure for providing broadband access is viewed from a complex system perspective. In determining the philosophical position for the research, a two dimensional framework by Snowden and Stanbridge (2004) is used to position the modelling approach within "Order – Un-order" ontology and "Rules – Heuristics" epistemology.

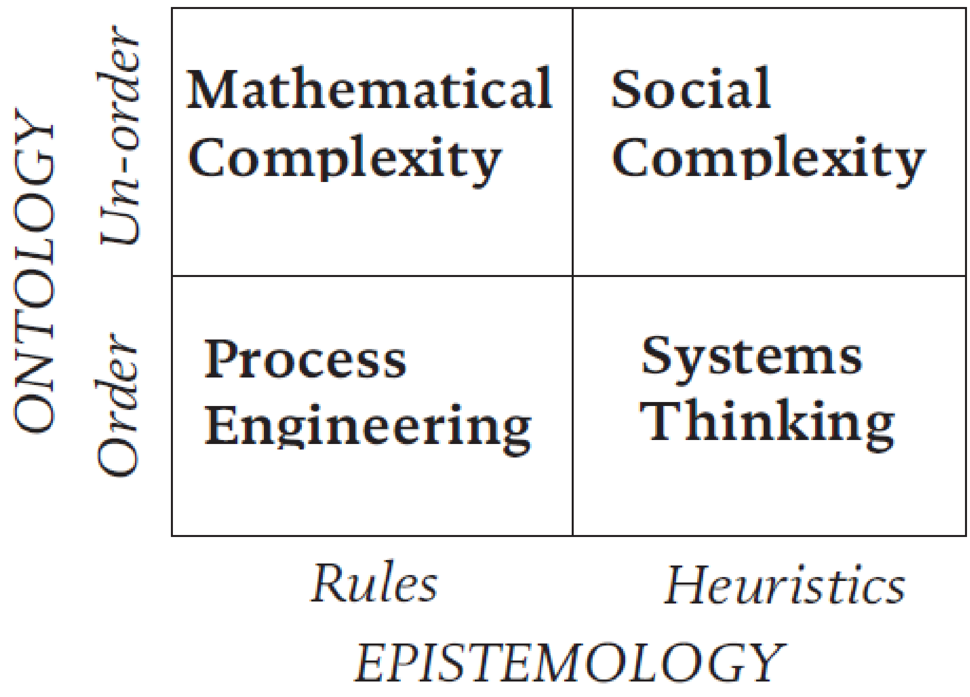

Figure 1-1 The Landscape of Management (Snowden and Stanbridge, 2004)

From the four quadrants (Snowden and Stanbridge, 2004) the proposed research falls into the Mathematical Complexity domain (Figure 1-1). In terms of ontology, the investigated phenomenon of developing an NGN infrastructure is viewed as an unordered system with a higher degree of inexplicit relationships between elements. From an epistemological perspective, the proposed model is an attempt to represent a system with a low level of ambiguity and clearly formulated set of actions from an NRA.

One of the research's objectives is to formulate behavioural rules of stakeholders (operators, users, regulators) on the basis of ABM to represent the characteristics of the system. These rules would help NRAs to articulate decisions related to IS and can be used for creating a framework where the external determinants of IS are viewed as objective external factors and where the reaction of stakeholders is considered within a social setting. With this view the proposed research inclines towards a realist ontology, which is also backed up with the following argumentation.

Firstly, the proposed context of development of alternative networks to facilitate infrastructure based competition is perceived as external to the decision support framework. Infrastructure Sharing is thus viewed as a reaction to external factors, such as growing demand on the one hand and scarcity of man-made resources on the other. Creating a decision support framework aims at the “formalization of underlying reality” (Mir and Watson, 2001). This also suggests the second reason for critical realism, with the external role of a researcher being more observer than participant. The observed phenomenon is already formulated in the business and regulatory environment which forces academic research to react and address the problem in a given format.

Thirdly, critical realist epistemology assumes that the results of the research are replicable for a given set of initial data. The proposed decision support software tool suggests that a similar set of input data will generate similar output results. The final recommendations as the result of the decision support tool are meant to be replicable responses to contingencies without ideological actions of involved stakeholders and with contexts as the key to perspectives (Mir and Watson, 2001). Another reason in favour of critical realism is that a complex system perspective assumes that emerging interrelationships between agents in a system exist as a potential rather than direct causal correlation.

The philosophical approach for the proposed research is believed to fit into the notion of “structured ontology” (Bhaskar, 2013). Among the three layers of critical realism the scarcity of resources which constitutes a causal power and has real consequences for users is taken as real, i.e. existing objectively. The increased competition for known natural and man-made resources among users and their reaction, forced or voluntary, to share available means, is viewed as actual and represents the domain of the events generated by causally operating structures (scarcity of resources). The empirical domain of critical realism constitutes perceptions of various stakeholders, i.e. users, businesses and regulators, towards the concept of IS which leads to individual responses (regulatory policies, business arrangements, formalised public demands). The proposed research approach aligns with the three domains and can be justified on the grounds of critical realist epistemology.

Another argument in favour of critical realism is the notion of causality and correlation. Critical realism assumes that causality exists as a potential rather than a direct correlation between phenomena. The complex system perspective applied in this research realises the power of emerging links between external and internal determinants of IS. The emerging nature of relationships between multiple factors constitutes a potential of multivariant scenarios with unique correlation outcomes in each case. This view distinguishes the current research from stronger forms of positivism and brings it closer to relativism. However, even though a complex system perspective does consider socially constructed relationships between actors, it also takes into account objective determinants. The mix of objective and socially constructed factors differentiates the research approach from constructivist epistemologies.

1.5 Research Contributions

The research investigated the potential for innovation in network competition via IS in the area of telecommunication systems. The study uses a computational modelling approach and examines three methods of network competition through three scenarios: the Greenfield scenario is the creation of a new network infrastructure (ducts, poles, wires and cables); the Bitstream scenario is the introduction of service based competition using an existing network infrastructure; whereas the Brownfield scenario gives operators the ability to integrate new cables and wires into an existing physical infrastructure (ducts and poles). The model runs these scenarios in a virtual landscape of supply and demand (an economy using the networked infrastructure) into which the regulator can intervene with policies that generate competition to improve service outcomes.

1.5.1 Contribution to Academia

The outcomes of the research contribute to the academic domain as this study uses a unique approach, (i.e. a tailored agent-based simulation), using a complex system perspective on a regulatory field in a particular network industry. Simulation experiments provide an opportunity for other researchers to analyse the dynamic co-evolution of infrastructure networks and groups of users with individual and group behavioural characteristics. Infrastructure development scenarios contribute to academic debate on the theory of the “Ladder of Investments”. All three scenarios, i.e. Bitstream, Brownfield DPA and Greenfield, represent three distinct rungs of the ladder. Simulating the behaviour of operators using an ABM approach can provide a completely new bottom-up and spatial perspective on the validity of the theory of the “Ladder of Investments”. Based on outcomes of the Empirical Project (EP), a theory of IS can be developed which would test and describe a general process of alternative infrastructure development on the basis of existing ones. A more detailed description of theoretical contributions is summarised in Section 8.1 Theoretical Contributions.

1.5.2 Contribution to Practice

Built on a concrete inquiry by the UK telecom regulator Ofcom, the decision support software tool offers an empirical contribution to regulatory practice. The purpose of the model is consistent with Broadband Delivery United Kingdom (BDUK) national and European (Digital Agenda) initiatives, and able to assist in establishing a regulatory framework for tailoring detailed implementation plans. The model provides a test bed for regulators who can run simulations, test assumptions under different conditions, and formulate strategies. The proposed model provides a significant empirical contribution as it offers an ABM framework realised in a software tool to represent IS in telecommunication.

Bringing together the behaviour of different user subgroups on the demand side and infrastructure development scenarios on the supply side in one model offers a methodological contribution to research practice. The novelty of the research is in the utilisation of different research methods (simulation, statistical, ABM) which widens the potential contribution effect for the research community. The software prototype is a hybrid method with ABM for user behaviour, simulation and visualisation techniques for infrastructure modelling, and statistical distributions for users' classification and probability of actions, and economic framework for cost analysis. The model also offers a methodological contribution to regulatory and business practice as it reinvents and reviews traditional Greenfield, Brownfield and Bitstream scenarios in developing telecommunication networks.

A more detailed description of methodological and empirical contributions is summarised in Sections 8.2 and 8.3.

1.6 Structure of the Thesis

First, the thesis identifies the positioning of the research and establishes its scope, boundaries and the potential research gaps in academic domains. The positioning study (PS) maps this study against theories and academic concepts in the areas of regulation, decision making (DM), innovation, business models of IS and complex systems.

The following section "Systematic Literature Review" further investigates the topic of IS in academic, business and regulatory literature domains with the intent to identify determinants of IS in relation to major stakeholders, i.e. users, businesses and regulators.

Section 4 "Research Method and Data Description" provides a full description of the research design made up of the decision support software model. This section also contains a description of the impact plan for engagement, dissemination, exploitation and evaluation of the research outcomes.

Next, the actual configuration and description of the decision support software prototype is given in Section 5. Results and outcomes derived from software simulation are presented in Section 6, and further discussed in Section 7. Theoretical, methodological and empirical contributions of the research outcomes are summarised in Section 8. Section 9 provides evidence of engagement with practice and evaluation of the impact of the research on organisations, economy, society and individuals within the “Impact Assessment”. These contributions and impact are formulated under a pre-agreed construct, boundaries and assumptions, which subsequently reveal the limitations of the proposed research approach. These limitations are discussed in Section 10.

Section 11 summarises the ten major lessons learnt over the course of the research. Section 12 discusses the implications. Conclusions and potential for further research are presented in Section 13 “Conclusions”.

2 POSITIONING OF THE RESEARCH

This chapter represents a study of potential areas for further academic investigation and elaborates a proposed area for research. It reports on the results of an initial literature assessment which establishes a foundation for a decision support model for regulating IS in telecommunications.

2.1 Introduction

The main purpose of the Positioning Study (PS) is to discover potential areas for further academic research. Specifically, the PS aims to identify new research dimensions of traditional academic domains, find innovative approaches from an inter-disciplinary perspective, provide a rationale for the research and formulate review questions for a detailed literature review.

The PS elaborates business problems and the research question articulated at the stage of Problem Formulation. The research question was decomposed into thematic areas to identify domains for the initial literature assessment. The relevance of existing theories and concepts in each literature domain are critically examined to define a potential academic contribution and prospective research path for a doctoral thesis to address specific gaps in knowledge. The PS lays foundations for successive research steps and transforms the initial research question into review questions for a detailed literature investigation.

2.2 Scope

Positioning of this research began with the analysis of a business phenomenon and deconstruction of the research question formulated for this PS to investigate regulation methods as part of the concept of National Innovation Systems (NIS) and their impact on IS:

“What are the characteristics of a decision-making framework for INNOVATIVE regulation of Infrastructure Sharing in telecommunications using a complex systems’ perspective?”

The scope of the revised research question formulated for PS is presented in Figure 2-1.

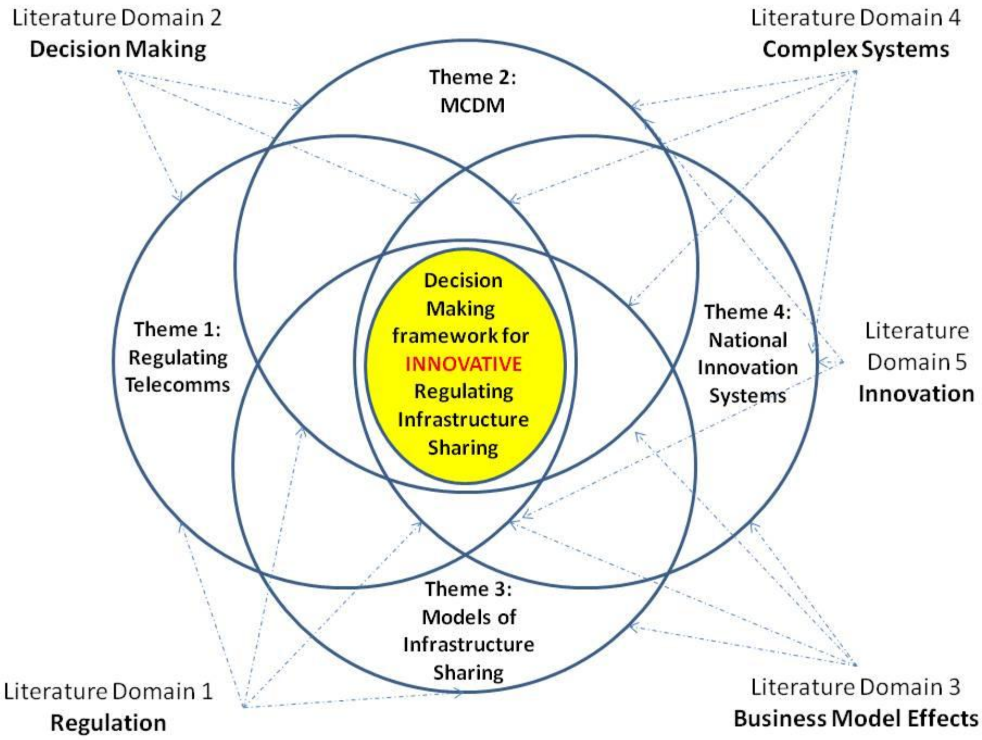

Figure 2-1 Scope of revised research question formulated for PS

To formulate an initial list for the preliminary literature investigation, keywords and phrases for database search engines were defined. After a preliminary literature scanning, further reading lists were narrowed down by using key search words and phrases, such as names of researchers, schools and concepts.

The scope of the initial literature assessment of the PS was defined using the following investigation approaches:

i. Use of material which is directly related to the professional area of the author. This comprises consulting reports, non-confidential memos and analyses, and membership subscriptions from professional organisations.

ii. Intelligent surfing through scientific electronic databases, such as Google Scholar, ScienceDirect, Emerald, Scopus, Web of Science, by using key research words and phrases.
iii. Advice and direct references from personal, professional and academic networking communities.
iv. Narrowing down the literature focus by virtual ‘joining in with academic debates’ which are relevant to addressing the research question, e.g. a debate between theories of the “Stepping stone” and the “Ladder of Investments”.

2.3 Literature

A collection of 204 publications was selected for the initial literature investigation (see Appendix A). The primary goal was to decompose concepts and theories arising from the research question, trace their provenance, and sift through them from the perspective of research domains.

Preliminary reading and identification of debate topics in five literature domains, i.e. (i) Regulation, (ii) Decision Making, (iii) Business Models of IS, (iv) Innovation, and (v) Complex Systems, introduced general theories and concepts. Further investigation of four overlapping themes, i.e. (1) Regulating Telecomms, (2) Multi Criteria Decision Making, (3) Infrastructure Sharing and (4) National Innovation Systems, revealed key debate areas and gaps in the academic literature providing a focus for this research topic.

2.4 Mapping General Theories and Academic Concepts

2.4.1 Regulation

The first wave of regulatory transformations (1880s-1980s) represented telecommunication monopolies under centralised regulation (Noam, 2010;

Horne, 2013). The telecommunications industry was characterised by government controlled price regulation, infrastructure development, and universal service funding. Academic publications were dominated by the theory of natural monopoly (Hazlett, 1986) which viewed telecoms as monopolistic public utilities (Wenders, 1990). Regulation was based on the theory of public interest (Wenders, 1988), which assumed good intentions of regulators to avoid potential market failure and maximise economic and social outputs by natural monopolies. This theory was criticised and further developed by the economic theory of regulation of Stiegler, Peltzman and Posner (Wenders, 1988), who viewed regulators as politicians using the interests of stakeholders as a tool for their own re-election. The "capture" form of regulation theory further suggested that lobbying groups may hinder the independence of regulators by exercising election campaign incentives (Posner, 1974).

Snow (1988) studied various pricing methods of natural monopolies and predicted the significant influence of telecommunications on other economic sectors. Joskow and Noll (1981) also studied price regulations of monopolies, i.e. the Averch and Johnson model, optimal cost-price sustainability and variable pricing model, and concluded that the research area of price regulations generated the most 'progressive' studies on regulated monopolies due to their practical relevance for NRAs.

Garcia-Murillo and MacInnes (2001) applied the theory of bureaucracy, theories of organisations and theory of dependency to explain why the organisational structure of a regulator and historic ways of performing public services decrease their efficiency. Irwin and Ela (1981) analysed models of efficiency of government regulation and concluded that a model of static efficiency appeared to hinder innovation and development. The breakthrough in technology progress started to question the whole purpose of regulated monopolies (Irwin and Ela, 1981; Flacher and Jennequin, 2008).

The second wave is an era of deregulation and liberalisation (Foreman-Peck, 1985; Noam, 2010) which forced policy makers to respond and find new models of regulatory practices (Gillick, 1992). Regulation shifted from controlled to incentive practices to focus on the market performance indicators (Berg and Foreman, 1996). However, Egan (1988) claims that the concept of social welfare remained an important requirement under deregulation. The telecom infrastructure of monopolies was viewed as an 'essential facility', which is hard to replicate in terms of cost and regulatory policies (Renda, 2010). In liberalisation, the 'essential facility' doctrine was developed further in the theories of Stepping stone in the US and Ladder of Investments in Europe (Cave, 2006; Hazlett, 2006).

The third wave of regulatory transformation, i.e. transition from policy formulation to policy implementation, considered three major policy trends: (i) no regulation, (ii) temporary regulation and (iii) tight regulation of the industry (Melody, 1999; Stern, 2004). The third trend, based on the theory of market failure (Gómez-Barroso and Feijóo, 2010), justified an NRA's interventionist role to maximise public interest in situations when markets fail to do so. Dassler (2006) reviewed theories of regulatory interventions and regulatory governance to provide a theoretical foundation of governments' interventions. Even in countries with a history of free market regulation, the idea of stronger regulation required critical attention (Kiessling and Blondeel, 1998; De Streel, 2008; Huigen and Cave, 2008).

Certain studies analysed relationships between the deployment of new generation broadband networks, competition, access pricing and investments (Chang, Koski and Majumdar, 2003; Lebourges, 2010; Briglauer, Ecker and Gugler, 2012; Crandall *et al.*, 2013). Valletti (2003) reviewed the literature on the theory of access pricing of incumbent infrastructures and its effect on investments in new networks. Similarly, Cambini and Jiang (2009) conducted a research examination of approximately 60 studies to understand the connection between regulatory measures and investments in telecommunication infrastructure. The problems of the digital divide and universal service are examined in Gabel (2007), Levin (2010); Gulati and Yates (2012); Holt and Galligan (2013).

In a transition to the third wave, traditional research topics tend to adjust to new market and regulatory conditions (universal service, infrastructure development, access policy). New research areas develop geographically and present more insight into new economies (Flacher and Jennequin, 2008; Onishi and Tsuna, 2010; Waverman and Koutroumpis, 2011; Song, Zo and Lee, 2012). The topic of spectrum allocation re-emerges as the competition for scarce resources sharpens (Blackman, Forge and Horvitz, 2013). New concepts become evident with maturing cross-industry development and increased competition (Ypsilanti, D., Xavier, 1998; Economides and Tåg, 2012).

2.4.2 Decision Making

In their publication Buchanan and O'Connell (2006) trace back the general history of DM and development of managerial DM concepts, such as the economic theory of risk and uncertainty by Knight (1921) and organisational DM from the theory of cooperation by Barnard (1968). Köksalan, Wallenius and Zionts (2013) examine utility theory from the work of Edgeworth (1881), the contribution of Frisch (1926) with his theory of ordinal and cardinal utility, and the theory of subjective expected utility and probability by Ramsey (1931) and De Finetti (1937).

Von Neumann and Morgenstern (1944) viewed maximisation of expected utility as a sign of rationality of decision makers. Simon and Barnard (1947) argued that this rationality was not perfect but 'bounded' to derive not ideal but tolerable decisions. The impossibility of aggregating utilities of individuals into the sum utility of a group of those individuals was stated in the impossibility theorem by Arrow (1951). Fishburn (1970) developed utility theory by considering DM with and without probabilities. Edwards (1954) viewed expected utility from a psychological perspective and laid the foundation of his behavioural decision theory. In the 1980s, decision analysis and behavioural research was enriched with a sensitivity analysis by Von Winterfield and Edwards (1986). Kahneman and Tversky (1979) demonstrated, in their prospect theory, that human's behaviour under risk and uncertainty does not follow a rational model of economics. Decisions under uncertainty were also studied by Raiffa (1968) who developed the concept of decision trees.

Raiffa also wrote a report on utilities with multi-attribute alternatives within the project RAND (Raiffa, 1969). The multi-attribute analysis was further elaborated by Keeney and Raiffa (1976) who formulated multi-attribute utility theory (MAUT). Prior to MAUT, significant contributions to Multi-Criteria Decision Making (MCDM) include the Simplex method in 1947 (Dantzig, 2002), the efficient vectors and contributions to multiple objective mathematical programming (Koopmans, 1951), goal programming (Charnes, Cooper and Ferguson, 1955), the outranking methods within the ELECTRE-project (Roy, 1968), and the concept of multiple objective optimisation (Cohon, 1978).

Later developments include multiobjective decision analysis (Goicoechea, Hansen and Duckstein, 1982), interactive multiple objective DM (Aksoy, 1990), Evolutionary Multiobjective Optimisation (EMO) (Schaffer and Grefenstette, 1985), computer aided decision support systems (Ginzberg and Stohr, 1982), and heuristics methods in DM (Zanakis, Evans and Vazacopoulos, 1989). The concepts of the Analytic Hierarchy Process and Analytic Network Process introduced by Thomas Saaty are reviewed in more detail in Section 2.5.2 as these methods appear to have practical applicability to address the research question.

2.4.3 Business Models of Infrastructure Sharing

Studies of IS in telecommunications have developed with increased competition for infrastructure elements with different life cycles. The oldest concept is spectrum allocation (Levin, 1982; McLauchlan and Westerberg, 1982). Various authors discuss topics of spectrum policies (Farquhar and Fitzgerald, 2003; Hazlett, 2003; Forge and Blackman, 2006), spectrum management (McMillan, 1995; Cave, 2010a), spectrum rights (Ting, Wildman and Bauer, 2005; Cave and Webb, 2012), and spectrum for mobile communications (Valletti and Cave, 1998).

The issue of spectrum sharing between land and satellite systems was raised in 1987 (Almond, 1987). The majority of the literature on spectrum sharing appeared in the 2000s with the immense development of mobile communication. Foster (2008) prepared a publication on spectrum sharing for the GSR. Jorswieck *et al.* (2010) introduced the SAPHYRE initiative on infrastructure and spectrum sharing. Peha (2013) discussed simultaneous spectrum usage by many devices in occupied bandwidths. Daoud, Alanyali and Starobinski (2013) analysed the economic profitability of secondary spectrum access. Various researchers discussed cognitive radio technologies for spectrum sharing (Barrie *et al.*, 2012; Baldini *et al.*, 2013; Durantini and Martino, 2013). Blackman *et al.* (2013) suggested addressing spectrum sharing on a technical level (cognitive radio, mesh networking), a regulators' level (shift from exclusive allocation to flexible use) and a users' level (shift to self-management of the radio spectrum).

In fixed telecommunications, Criner (1977) defines sharing as a non-profit agreement on sharing the telecommunication costs between two users located in the same premises. Regli (1996) compares various infrastructure development theories ranging from state controlled cultural and technological protectionism, to more liberal notions of resource scarcity and the need for subsidisation, and to market driven concept of liberalisation. Liberalisation created the issue of LLU and other forms of IS (Meisel, 1992; Mudd and Starkey, 1992; Higham, 1993, 1994). Deregulation viewed IS as a major driver for infrastructure development and called for revision of an 'essential facility' doctrine (Renda, 2010).

Currently, the general IS paradigm represents a set of fragmented concepts viewed from various technological or stakeholders' angles. Each source offers a different approach to the classification of IS. The most recognised approach is given by the ITU (Best, 2008; Cohen and Southwood, 2008; Foster, 2008; Lazauskaite, 2008; Lefèvre, 2008; Schorr, 2008; Webb, 2008). The work by

Wyman (2007) gives an alternative IS taxonomy classified by depth, extent, reach of sharing and number of participants. In contrast, Frisanco *et al.*, (2008) present a taxonomy of mobile IS consisting of business, technology and geographic dimensions.

The universal approach by Frisanco *et al.* (2008) allows the combining of separate IS studies into one model. It is flexible enough to accommodate studies on unbundling (Crandall *et al.*, 2013; Deshpande, 2013), co-investment options (Egan, 1990; Bourreau, Cambini and Hoernig, 2012; Cambini and Silvestri, 2013; Schneir and Xiong, 2013), mobile infrastructure sharing (GSMA, 2010), spectrum sharing (Quer *et al.*, 2012), roaming (Fabrizi and Wertlen, 2008; Infante and Vallejo, 2012), MVNO (Shin and Bartolacci, 2007; Banerjee and Dippon, 2009; Shin, 2010), and third party infrastructure providers such as Openreach in the UK (Cadman, 2010).

2.4.4 Innovation

The history of telecommunications is built upon continuous innovations since the invention of the telephone (Van Duijn, 1981) until the rise of the public Internet (Hart, Reed and Bar, 1992). Countries select their own innovation paths either as pioneering leaders or catching up imitators (Madden and Savage, 1999). Innovations in Information and Communication Technologies (ICT) became the major economy drivers from the 1980s and launched “the fifth long wave” of economic development (Castellacci, 2006).

Kondratieff’s ‘long waves’ of economic development were researched in various studies (Wonglimpiyarat, 2005; Korotayev, Zinkina and Bogevolnov, 2011; Grinin, Devezas and Korotayev, 2012). Schumpeter further developed Kondratieff’s theory and formulated the theory of innovation (Hermens, 1941). Schumpeter’s theory explains “swarms” of innovations from a new ‘long-wave’, which abolish outdated products in ‘creative destruction’ (Wonglimpiyarat, 2005; Papenhausen, 2008) and initiate a shift towards a new economic cycle.

Nelson and Winter (1977) provide a summary of the most influential innovation theories from the perspective of economic theory of production and criticise the production function approach for neglecting uncertainty of innovation. They also review studies on the profit-maximising firm and the effect of Research and Development (R&D) on firms' profits. Nelson and Winter (1977) view innovation from both macro and micro economic perspectives and claim that innovation has its internal logic and way of development caused by the natural progress of science. As for diffusion of novelties, they point out two ways for companies to adopt new products, i.e. by pioneering their own or imitating another company's innovations.

Certain studies are dedicated to competition and its influence on innovation. McDaniel (2000) illustrates how competition positively affects firms in adopting novelties to increase profitability. However, van Cuilenburg and Slaa (1994, 1995) conclude that competition in a local loop positively affects innovation only during deregulation of a monopoly. With the increase of competition in a local loop, innovation may decrease. Stylianou (2011) confirms that an excessive level of competition in telecommunication can adversely influence innovation. Tang (2006) found that competition with a high probability of quick product substitution is negatively related to innovation. Teece (1992) mentions that under increased competition, integration within and between firms creates conditions when companies can be rivals in a retail market and partners in R&D (also Davidson, 1987).

Various researchers have studied the regulation of industries and R&D to assure the competitiveness of national economies. Bourreau and Doğan (2001) review the theory of economic efficiency and its static and dynamic forms. The authors consider the role of NRAs in regulating industry profits and entry conditions. Edquist and Hommen (1999) study complex interdependencies between stakeholders based on the theory of 'interactive learning', and the evolutionary and institutional theories of innovations. The 'interactive learning' theory considers interaction as a learning exchange between stakeholders. Evolutionary theory compares innovations to a process of natural selection in biological ecosystems (Nelson and Winter, 1977). Castellacci (2006) distinguishes between techno-economic and socio-institutional systems of innovation and provides a detailed analysis of institutions and their influence on innovations.

Sharif (2006) defines National Innovation Systems (NIS) as a composition of institutions and actors that participate in a country's adoption of technological novelties and also compares different NIS approaches from a 'social constructivist' point of view. Fagerberg and Srholec (2008) studied innovation systems in 115 countries and confirmed a strong correlation between high income per capita and solid innovation systems. A more detailed literature review on NIS is presented in Section 2.5.4 as this concept appears to address the research question.

Regulation of innovation in telecom is studied in Harris (1990); Zanfei (1993); Van Cuilenburg and Slaa (1994, 1995); Bourreau and Doğan (2001); Stylianou (2011). Bourreau and Doğan (2001) review studies on asymmetric and symmetric regulation and conclude that discriminatory regulation provides more innovation incentives for new companies, whereas incumbents benefit from regulated competition. The authors view standardisation policies as regulatory tools to constrain 'predatory innovation' and present evidence that price-cap regulation of both incumbent and new operators provides more incentives for innovation.

2.4.5 Complex Systems

Along with the history of complex systems (Sweeney and Griffiths, 2002), the proposed study is focused on the complexity theory (Dillon, 2001; Abraham, 2011). Complex systems have their roots in the chaos theory (Waldrop, 1993), systems theory (Ashby, 1957; Forrester, 1961; Nicolis and Prigogine, 1989), genetic algorithms (Holland, 1995; Mitchell, 1998), network theory (Newman, 2010), and concepts of emergence (Holland, 1998). In this study, the complex system's literature is investigated from the DM, regulation, telecommunication and innovation perspectives.

In DM, hybrid forms of MCDM and complexity, e.g. VIKOR, were developed (Opricovic, 1998; Yang, Shieh and Tzeng, 2009). Beck *et al.* (2008) applied a combined approach of dynamic multi-objective optimisation and ABM for planning energy networks. ABM and DM methods were considered in Zia and Koliba (2013) for formulating government transportation policy, in Nilsson and Darley (2006) for manufacturing and logistics operations, and in Rigopoulos *et al.* (2007) for payment systems. Milano and Lombardi (2014) analysed the hybrid techniques of Machine Learning, Game Theory and Complex Systems.

Chappin and Dijkema (2010) use ABM to assist regulatory decision makers to assess transition alternatives in energy infrastructures. Grove and Baumann (2012) apply a complex system perspective for comparing distinct service and integrated infrastructure/service providers. Brown *et al.* (2004) analyse interdependencies between infrastructures, decision makers, and individuals, to mitigate the risks of infrastructure failures. Dobson *et al.* (2007) use a complexity approach for analysing sequential failures in power generation and transmission systems on a global scale. Herder, Bouwmans and Dijkema (2008) apply complexity theory to review three case studies of infrastructure development using an integrated approach of physical and actor network design.

In innovation, Silverberg (2005) tests the theory of long waves to explain the inconsistency of periodic patterns and their inability to predict. Applying a complex dynamics approach, the author concludes that Kondratieff's waves do not exhibit a periodic relationship but can be explained by the power-law phenomenon. Ahrweiler (2010) views innovation as an emergent characteristic of complex regional networks of universities, businesses, research institutes and regulators. Katz (2006) uses a complex system approach to NIS of European and Canadian provinces to develop scale-independent innovation indicators for better DM. Russo and Rossi (2009) combined ethnographic questionnaires and social networks analysis to review an innovation programme in an Italian region.

2.5 Main Contributions and Debates

The main debate in telecommunication policy is built around the question: What is the best regulatory model for the 21st century and to what extent should a government intervene? The summary of the debate is presented in Yang *et al.* (2013) who overview three current regulatory models in telecommunications: (i) an extensive deregulation and liberalisation model (US), (ii) a strong government participation model (Japan, South Korea, China), and (iii) a mixed model of deregulation and government interventions (Europe). The deregulation model focuses on competition and provides short-term regulatory results affecting static economic efficiency. The interventionist model focuses on dynamic efficiency and pursues long-term results from formulated market, industry, education, and innovation policies. Although the European mixed model may appear to be a consensus between the US and Asian regulatory models, the debate still remains on what regulatory model is preferable and what other factors (globalisation, new business models such as e-business) explain the differences in regulatory outcomes.

Debate in the DM field is based upon applicability and trade-offs of each out of numerous MCDM methods. Velasquez and Hester (2013) summarise, review and debate over 11 MCDM methods. Critics and proponents of each method highlight issues of dealing with uncertainty, ease and convenience of use, amount and quality of data needed, scale and area of a problem, and the ability to generate outcomes as standalone or with other methods. In general, opponents agree that a combination of different MCDM methods for solving one problem can overcome the deficiencies of a single method.

The concept of IS is still new in business and academic domains and consists of several topics. The common debate slogan for all the topics can be expressed as follows: “To Share or Not to Share”. In spectrum allocation there is a growing debate on the revision of policies, i.e. spectrum as private versus public common, de-licensing of certain bandwidths, secondary and simultaneous use of spectrum (Blackman *et al.,* 2013). Regarding mobile, the debate has emerged from cost efficiencies of sharing to IS agreements (joint ventures, strategic alliances, 3rd party providers) and regulating IS (GSMA, 2010). For mobile operators the question remains whether to allow an MVNO on an own network (Shin and Bartolacci, 2007; Banerjee and Dippon, 2009; Shin, 2010). The biggest debate in building an NGN is the extent of co-investment options and the interventionist role of government in infrastructure development Bourreau *et al.* (2012). The academic area discusses infrastructure-based versus service-based competition for infrastructure development and debates over the universal use of the “Stepping stone” theory (Hazlett, 2006) and issue of unbundling (Crandall *et al.*, 2013; Deshpande, 2013).

In the area of NIS there are several debate topics. Carlsson *et al.* (2002) compare NIS to other approaches of innovation (“input/output analysis”, “development blocks”, “diamond”, “sectoral innovation systems”, “local industrial systems”, “technological systems”). The authors argue that the NIS approach focuses more on comparative static data and less on a system’s dynamics. Hekkert *et al.* (2007) also criticise the static approach of NIS and dispute their focusing on macroeconomic issues and neglecting the Schumpeterian ‘creative entrepreneur’. Weber and Rohracher (2012) argue that NIS concentrate only on the supply side and overlook the production and consumption sides. Generally, the NIS approach is not a universal concept and generates unique results for every country. Chaminade, Intarakumnerd and Sapprasert (2012) summarise that, unlike the neo-classical approach, the NIS approach does not generate ‘right’ or ‘wrong’ answers but looks for adaptive, ‘path dependent’ solutions.

The following sections look at the overlapping themes in more detail.

2.5.1 Regulating Telecomms

The “Stepping stone” theory (Hazlett, 2006) suggests that open access would be a starting point for entrants to build their own infrastructure. Hazlett proves that growth in new wirelines by new entrants after 1996 was less than estimated. The obligatory network sharing did not facilitate the development of new infrastructures, which led to the abandonment of the Telecommunication Act in 2004. From the “Stepping stone”, the US regulation shifted to “Access holidays”, which brought an immediate rise of investments in new infrastructure (Renda, 2010).

The drawbacks of the “Stepping stone” theory were considered in the theory of the “Ladder of Investment”. Cave (2006) concludes that regulators can set appropriate access prices to replicate infrastructure both by incumbents and new entrants, and limit the time for entrants to generate enough revenue for constructing their own networks. Both conditions create necessary incentives for new operators to climb the “Ladder of Investment”. This theory has received wide practical implementation in the EU. Bourreau, Doğan and Manant (2010) state that by 2005 the “Ladder of Investment” concept was used in most of the EU countries. Cave (2010b) also found that “Ladder of Investment” could be applied for fibre networks.

However, there is strong criticism of this concept. Bourreau, Doğan and Manant (2010) provided empirical evidence that the ‘Sunset Clause’ condition of limiting time for service-based competition showed controversial results. The theory seems to be valid for urban areas but needs further research for rural areas. Recent research on the “Ladder of Investment” by Bacache, Bourreau and Gaudin (2014) found no empirical evidence of the relationship between the number of unbundled lines and the number of lines built as a new infrastructure.

2.5.2 MCDM

Due to its universality the Analytic Hierarchy Process (AHP) has been applied in regulation, resource allocation, and business strategy formulation (Giokas and

Pentzaropoulos, 2008; Ho, 2008; Subramanian and Ramanathan, 2012). As DM is required by many stakeholders, i.e. regulators, businesses, and users, AHP is suitable as a group DM tool (Saaty, 1977). Similarly to the proposed research, Toossi, Camci and Varga (2013) used AHP to assist decision makers with strategy selecting for energy transition policies. Nikou and Mezei (2013) apply AHP to identify customer decisive preferences in the successful adoption of new services in mobile telecommunications.

While AHP focuses on a goal and independent hierarchies, Analytic Network Process (ANP) (Saaty, 1996) treats DM structures as networks with interdependencies and feedback. This is vital as the current research intends to represent stakeholders as networks of users, regulators and businesses that constantly affect each other. Saaty (2007) uses both AHP and ANP for the further development of the theory of time-dependent DM. ANP has applications in various fields (Gencer and Gürpinar, 2007; Sipahi and Timor, 2010).

2.5.3 Infrastructure Sharing

Whilst thematic analysis on other themes narrowed down the focus from broader to more detailed topics, the IS literature opened up the debate. One explanation is that the topic of IS in telecommunications is still new in the academic domain. Database searches give results for IS either from other utilities or limited information on certain IS options (network or spectrum sharing). The second reason is that the topics of regulation, DM and innovation are usually formulated at a higher level, viewing IS as a discrete business case.

A complex system's perspective of emerging interdependencies between various infrastructures in highlighted in Rinaldi, Peerenboom and Kelly (2001) who use the US 1997 report on Critical Infrastructure Protection as a foundation for their research. The authors present eight types of critical infrastructures, which directly affect the country's defence and economic performance, as Complex Adaptive Systems (CAS). Rinaldi *et al*. introduce a six dimension model of interdependencies between critical infrastructures in which change occurs as a learning process between systems. The proposed approach is a good reference framework for addressing the research question as IS in telecommunications exhibits clear interdependencies with other infrastructure systems.

Tran *et al*. (2014) in the report issued by the Infrastructure Transition Research Consortium (ITRC) introduce NISMOD – a National Infrastructure System-of-Systems Model for analysing, planning and executing infrastructural projects in the UK. Seventeen infrastructure development scenarios for five major economic infrastructures (energy, transport, water, waste and ICT) are developed in four strategy portfolios.

Most IS concepts (unbundling, passive and active sharing, MVNO, 3rd party infrastructure providers) fit into the Increasing System Efficiency strategy. The co-investment sharing scheme falls under the Capacity Expansion pillar. The issue of spectrum sharing falls under the New Services and Planning perspective. Further to the ITRC project, the Transforming Utilities' Conversion Points (TUCP) project developed a new ontology for the description of infrastructure systems connected directly to the services extracted from that infrastructure (Varga *et al.,* 2014). The methodology used by TUCP was ABM.

2.5.4 National Innovation Systems

The performance of NIS was analysed in various studies. The Organisation for Economic Co-operation and Development report (OECD, 1997) compares definitions of NIS and concludes that formalised and distributed knowledge comes from many sources, i.e. companies, universities, research institutions, and regulators. Lundvall (1992) views NIS from the perspective of theory of innovation and interactive learning. Nelson (1993) analyses differences in NIS among countries and concludes that failure to implement NIS in a country may lead to economic failure. Japan is benchmarked as having one of most successful NIS in the 1980s (Freeman, 1989). Patel and Pavitt (1994) analyse OECD countries and note significant differences in NIS performance due to scaled implementation or given regional specialisation. Metcalfe (1994) summarises that regulation policy is a core part of NIS, which keeps the continuous movement of "experimental variety" and "economic selection".

In the 21st century the concept of NIS tends to grow beyond national borders due to the globalisation of Economies. Carlsson (2006) illustrates how internalisation of innovation gradually overcomes barriers caused by national laws and industrial policies. Freeman (2002) analyses the relationship between NIS and economic performance in Britain, the US and emerging economies in the 18th - 20th centuries. He concludes that in the 21st century innovation will develop on national, regional and international levels due to the global nature of production. Hemphill (2013), while studying the innovation strategy of the Obama administration, raises the question of the global competitiveness of the US innovation strategy.

2.6 Research Gaps

A universal classification of IS methods and therefore a general approach to researching the phenomenon is missing. Existing empirical studies concentrate on either mobile or fixed IS. The spectrum sharing is treated separately. A generally accepted taxonomy of active and passive IS seems to be applicable only for mobile telecommunications. Existing studies in IS are fragmented into topics of varying maturity (co-investments, unbundling, MVNO, spectrum sharing and 3rd party network providers).

Existing studies on IS report results on the marginal effect of a certain method on a company's performance or economy but do not focus on synergetic and network effects of various IS types. The majority of studies take a business perspective and derive specific suggestions for CEOs and broad recommendations for regulators. However, there is a growing demand for studies that would utilise a regulator’s perspective on IS and consider the cumulative effect of combined strategies at the macro level. Current studies mostly concentrate on one industry infrastructure but do not factor interdependencies with other critical infrastructures. A complex system perspective to analysing emerging interrelationships of infrastructures with other actors is present in energy studies but not witnessed in telecommunications.

Traditional areas of telecommunication regulation are well researched and continue to attract academic attention. New telecommunication trends urge governments to move to 4th generation regulation (Horne, 2013), which should address policies on governing ‘digital ecosystems’. New academic research on regulating complex ecosystems, consisting of users, businesses and ‘things’, is required. New forms of regulations, such as consultations, partnerships, co- and self-regulations, open new research opportunities. The convergence of media, ICT and social networks raises new technological, security and regulatory issues and creates demand for new studies. Generally, the convergence of industries and increasing complexity of interrelationships between stakeholders creates a whole new area for cross-industry and multi-disciplinary research studies on telecommunication regulation.

Unlike other fundamental disciplines, academic research on DM is still in a sharp growth stage of its life cycle. Keeping in mind the multiple dimensions of DM methods (e.g. MAUT, AHP, Data Envelopment Analysis (DEA), etc.), numerous versions within one method (e.g. Conventional AHP, Ideal Mode AHP, ANP, etc.), universal ability for cross-industry and multi-disciplinary applications, further opportunities lie in determining new areas for investigation. MCDM continues to develop both in theoretical and practical dimensions. Fundamental research extends existing knowledge by combining theories from within and outside of MCDM. Practical implementations are found in potentially any industry. A database search on AHP/ANP methods in telecommunications returns thousands of publications. However, there is a research gap in applying MCDM methods to the particular topic of IS in general (less than five publications found in electronic databases) and IS in telecommunication in particular.

Out of the numerous research opportunities in the area of NIS, a particularly interesting research gap is found in Gallouj and Zanfei (2013). The author mentions that the topic of innovation in delivering public services is less researched. With regard to policy making, the NIS approach traditionally generates recommendations for the regulation of various aspects at a macro level. However, the proposed research aims at creating a methodology for NRAs for making decisions on a country level and delivering public services on regional and municipal levels. For example, a central mandatory policy to allow shared use of ducts will require local authorities to process licences and permits. A potential research gap can be investigated with the goal of bridging innovative IS practices with corresponding innovative public services within one NIS.

2.7 Key Academic Learning Points

Research on government policies shows that there is no universal “one size fits all” model of regulation. Among three generally recognised models of regulation (free market regulation, interventionist role of government, mixed model of liberalism and interventionism) countries define their own level of government participation and formulate distinct models that are “fit for purpose”. These phenomena are explained by the theory of ‘regulatory interventions’ and its two schools of market-driven and non-market-driven approaches (Dassler, 2006).

The theory of public interest and economic theory of regulation (Wenders, 1988) found major academic concepts in the area of regulation. However, the theory of market failure continues to be the dominant theoretical concept that justifies interventionist role of governments in maximising public interest (Gómez-Barroso and Feijóo, 2010).

The efficiency approach to analysing regulatory models suggests that the concept of dynamic efficiency of regulation (interventionism) prevails over static efficiency (liberalism) as global competition between countries and regional specialisation of national economies increases (Yang *et al.*, 2013).

New technological breakthroughs create opportunities and also new challenges, e.g. digital divide as it relates to Internet-based services. With the shift away from traditional voice services, fundamental theoretical concepts such as theory of universal service do not become outdated and are successfully modelled to address new forms of digital inequalities (Holt and Galligan, 2013).

Academic studies related to regulatory and public issues serve the interests of certain groups of scientists, policy makers and demographic groups, and in certain cases cannot be impartial. The "capture" form of regulation theory suggests that various objectives of different groups may hinder independence not only of regulators but also political scientists (Posner, 1974).

In the area of MCDM applying one certain DM method to solving one particular research problem will not be enough as different DM methods may generate different outcomes due to known limitations. A more thorough approach would require applying a bundle of MCDM methods to offset the limitations of a single DM method (Velasquez and Hester, 2013).

A distinct academic area of Infrastructure Sharing does not yet exist. The topic of IS is viewed in different infrastructure development theories and 'essential facility' doctrine as an implementation option or recommendation for regulation. Existing studies on IS are fragmented and generally accepted taxonomies of IS methods vary across different researchers (Wyman, 2007; Frisanco *et al.*, 2008; Schorr, 2008). The academic terminology on the topic of IS varies across different sources, which is important for conducting an accurate systematic literature review. It is vital to use different search combinations, such as "Infrastructure sharing", "Facilities sharing", "Common use", etc.

Applying a complex system perspective to the topic of IS is an emerging area of research as interdependencies between infrastructures, businesses, users and regulators are increasing (Rinaldi *et al.*, 2001; Tran *et al.*, 2014).

2.8 Review Questions

The following revised review questions for systematic literature review (SLR) are formulated after incorporating recommendations from Review Panel members.

The main literature review question (MainQ) is:

> **What aspects of inter-dependent shared infrastructures and stakeholders, e.g. users, businesses and regulators, are required for the regulatory decision-making of infrastructure sharing?**

The first sub-question (SubQ1) for the SLR is:

> **“What common sharing principles and sharing models are used in different infrastructure systems, i.e. water, energy, telecommunications and transport?”**

The second sub-question (SubQ2) is:

> **“What influential factors (economic, geographic, demographic, environmental, social, political, etc.) are determinants of sharing models and sharing principles in infrastructure systems?”**

The third sub-question (SubQ3) is:

> **“What common sharing principles and sharing models are relevant for regulatory decision-making in infrastructure systems?”**

2.9 Summary

In this PS, theories and concepts in selected academic fields were analysed with the aim of identifying potential research gaps and opportunities for the topic of regulating IS in telecommunications. A multi-disciplinary approach of the analysis offers the following conclusions.

As an academic concept, IS is still in the early stages of its formulation. Clear boundaries and definitions of IS in telecommunications are not precisely fixed in academic literature. Taxonomies from business and managerial papers are flexible and ambiguous. There is a research gap in the theorisation of IS.

The topic of IS is a fragmented academic field which consists of different sub-concepts of various maturities. Traditional older sub-concepts, e.g. LLU, provide more academic evidence, whereas newer concepts, e.g. MVNO and roaming, offer wider research opportunities. There is a need to find a combined approach to normalise knowledge diversity.

The field of IS is very heterogeneous due to the physical and conceptual nature of IS options. This suggests that academic works focusing on one particular sub-concept provide an incomplete picture and omit other options. This raises the need for a universal research approach which would map all available IS sub-concepts.

The subject of IS falls under areas of regulating telecommunications and developing infrastructures. General theories on regulation and infrastructure development provide the initial foundation for approaching the research problem but do not directly apply to addressing the research question.

MCDM methods for regulation are mostly focused on static interrelationships between alternatives and criteria. However, a complex system perspective to MCDM, which considers emerging and dynamic interdependencies between actors and observables, requires more academic attention.

Although multi-disciplinary research approaches to building DM models with complex systems perspectives are witnessed in academic publications, this PS has found no evidence that there is a particular research on a DM model for regulating IS in telecommunication.

The PS suggests that there is a gap between academic findings on regulation and delivery of corresponding public services as a result of these findings.

After completing the PS, the Review Panel suggested excluding the NIS concept from further research and applying a multi-disciplinary approach of MCDM, IS, and Regulating telecommunications with the use of a complex systems perspective for further SLR.

3 SYSTEMATIC LITERATURE REVIEW

3.1 Literature Domains and Themes

This chapter represents the positioning of research within existing literature domains. Based on the review questions formulated in Section 2.8, the following literature domains and themes were identified for the SLR (see Figure 3-1 Literature domains and themes for SLR). Although the DBA research aims at investigating the topic of IS in wireline and wireless telecommunications, the SLR will also look at industries with similar network characteristics, i.e. transportation, energy, and water (the Literature Domain "Infrastructure Industries"). The scope of the SLR will include man-made infrastructures.

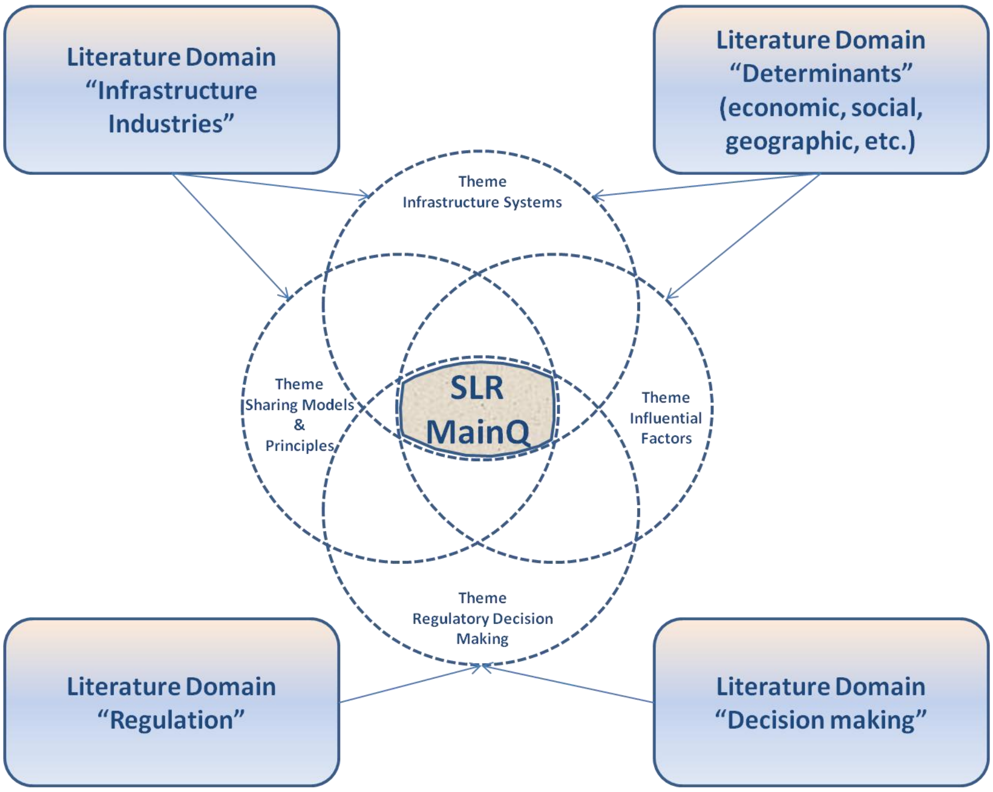

Figure 3-1 Literature domains and themes for SLR

The domain of Regulation represents the literature on formulating and exercising government policies in telecommunications and other infrastructure utilities. The literature domain of Decision Making is important to trace the provenance of MCDM methods to be used in the proposed research. The literature domain Determinants provides information on quantitative and qualitative economic, demographic, geographic, business development, environmental, social, and technological variables relevant to a certain country, region or industry sector.

The proposed four literature domains define the following areas for further thematic development: Sharing models and principles (S1), Infrastructure systems (S2), Regulatory decision making (S3), and Influential factors (S4) (Figure 3-1).

The thematic area 'Sharing models and principles' (S1) deals with common sharing concepts, e.g. joint use of facilities, shared and collaborative use of premises, co-opetition, etc. The thematic area (S2) 'Infrastructure systems' defines the context of infrastructures and utilities, such as water, energy, telecommunications, and transportation. The theme (S3) 'Influential factors' defines the scope of the external and internal environment. The area of 'Regulatory Decision Making' (S4) is defined by the literature domains of Regulation and Decision Making and by specifically looking at the nature of government interventions in certain sectors.

The overlapping area of the themes 'Sharing models and principles' and 'Infrastructure systems' ($S1 \cap S2$) provides answers for SubQ1 and results in classification of IS methods used in water, energy, telecommunications, and transportation. The overlapping area of the themes 'Sharing models and principles', 'Infrastructure systems' and 'Influential factors' ($S1 \cap S2 \cap S3$) addresses SubQ2 and aims at determining economic, geographic, demographic, environmental and other determinants of IS methods. The interception of 'Sharing models and principles', 'Infrastructure systems' and 'Regulatory decision making' ($S1 \cap S2 \cap S4$) determines the literature on the subject of government policies for IS and addresses SubQ3. The answer to the main question (MainQ) is given by the literature defined by the overlapping areas of all four thematic areas ($S1 \cap S2 \cap S3 \cap S4$).

The following section explains the methodology of the SLR.

3.2 Methodology

The main subject of the proposed doctoral research is a methodological decision support framework for NRAs to implement the most effective types of IS in wireline and wireless telecommunications. On the way to formulating the decision support framework it is important to synthesise and systematise existing academic and professional knowledge on sharing concepts in related industries. The starting point for knowledge synthesis is conducting an SLR of the existing body of knowledge.

3.2.1 Why SLR?

The SLR is preferable for several reasons. Firstly, the main objective of the proposed model is to provide methodological assistance in the area of decision support which requires 'best evidence' from diverse theoretical and practical sources. Secondly, building a model requires a multi-disciplinary approach of 'Infrastructure industries', 'Regulatory DM' and 'Influential determinants' with the use of heterogeneous sources of quantitative and qualitative data. Thirdly, an SLR is necessary as the proposed model must have strong theoretical and practical applicability. Fourthly, the area of IS, due to its relative novelty, may not have enough sources of academic origin in solely the telecoms sector.

3.2.2 Systematic Review Panel

To ensure the quality and objectiveness of the SLR, it is important to form a Review Panel consisting of recognised specialists in respective professional areas, methodology experts and academics. The following table represents the Review Panel members and their roles.

Table 3-1 Review Panel members

Person	Organisation	Involvement
Prof Liz Varga	Principal Research Fellow; Director of Complex Systems Research Centre, Cranfield University, UK	Lead Supervisor: Assisted in defining the literature review approach and provided feedback on draft of the review
Dr Palie Smart	Director PhD Programme; Reader in Corporate Responsibility, Cranfield University, UK	Advisor: to provide feedback on Systematic Literature review strategy
Prof Mark Jenkins	Director of Community for Strategy, People & Leadership, Cranfield University, UK	Advisor: to provide feedback on Systematic Literature review strategy
Prof Martin Cave	Deputy Chair of the Competition Commission, UK; Visiting Professor at Imperial College Business School, UK	Expert: to provide feedback on infrastructure systems and regulatory aspects from UK perspective
Prof Chris Kilsby	Professor of Hydrology and Climate Change, School of Civil Engineering and Geosciences, Newcastle University, UK	Expert: to provide feedback on the topic of infrastructure development and sharing practices in various infrastructure systems
Prof Tim Brady	Principal Research Fellow, Centre for Research in Innovation Management, University of Brighton, UK	Expert: to provide feedback on the topic of infrastructure development and sharing practices in various infrastructure systems
Ms Mary Betts-Gray	Business Information Specialist, MIRC, Cranfield University	Expert on literature search: supported the literature search strategy

3.2.3 Search Strategy

The overall process of identifying the relevant literature for the SLR is defined through selecting key search words and applying them to relevant electronic databases. Then the final set of literature is narrowed down through iterative processes of modifying search strings, applying inclusion and exclusion criteria for titles of the articles, abstracts and full texts, conducting a quality assessment and performing knowledge synthesis. Figure 3-2 represents the overall schematic process of the search strategy.

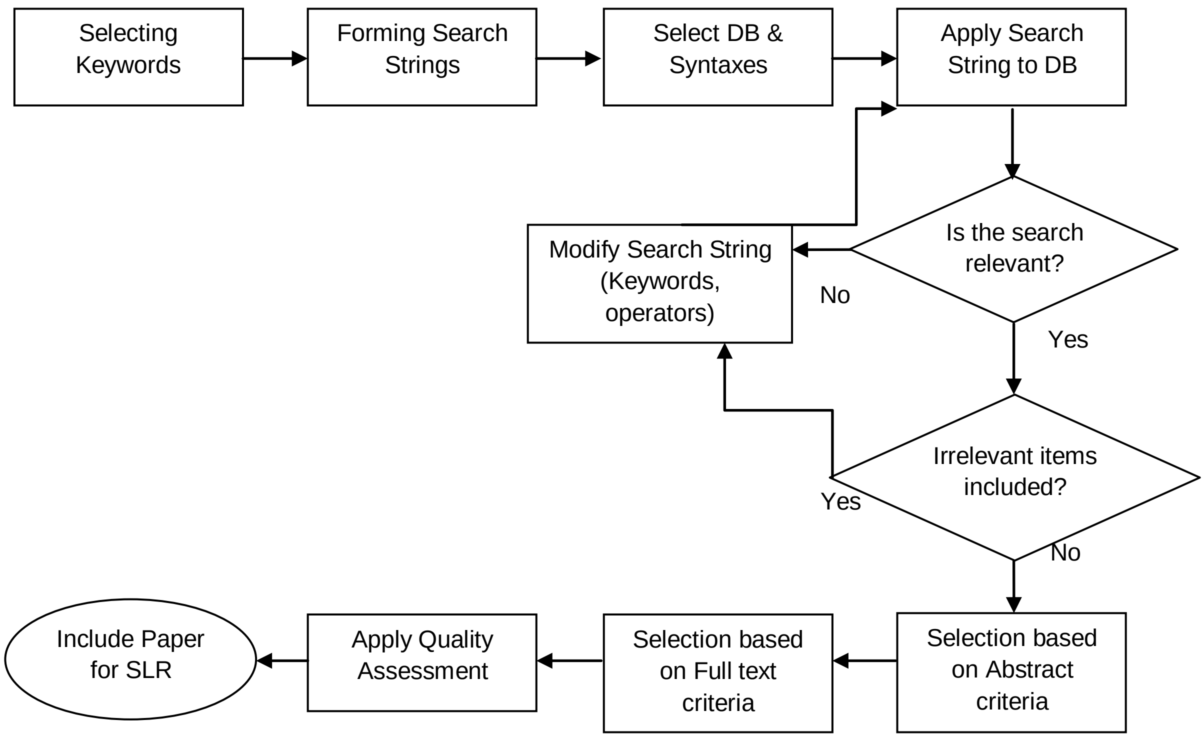

Figure 3-2 Schematic process of SLR

A set of keywords for each thematic area was formed for constructing relevant search strings and applying them to various databases with appropriate syntaxes. As different keywords produce results with different degree of relevance, the list of most relevant keywords for each thematic area was experimentally determined after several iterative searches. Table 3-2 represents a list and syntax of search strings which were used for the final selection of articles and papers for final SLR.

Table 3-2 List of the most productive search strings (experimentally determined)

Area	Search String
(S1) Sharing models and principles	**"joint use of facilit*"** OR **"infrastructure sharing"** OR "**common carriage**" OR **"infrastructure collaboration"** OR **"common pool of resources"** OR **unbundling** OR "**open access**" OR **sharrows** OR "**rights of way**" OR **MVNO** OR **roaming** OR "**shared resource pool**" OR **co?opetition** OR "**lane sharing**" OR "**sharing agreement**" OR "**network sharing"** OR "**RAN sharing**" OR "**tower sharing**" OR "**mast sharing**" OR "**site sharing**" OR "**spectrum sharing**" OR "**sharing models**" OR "**sharing principle***" OR "**shared use**" OR "**joint use**" OR "**mutual use**" OR "**shared usage**" OR "**joint usage**" OR "**mutual usage**"
(S2) Infrastructure Systems	**"water transfer"** OR **"water treatment"** OR **"reservoir system"** OR **(infrastructure NOT econom*)** OR **"public utilit*"** OR **"private utilit*"** OR **energy** OR **"power transmission"** OR **"power distribution"** OR **"gas transmission"** OR **"gas distribution"** OR **electricity** OR **transport*** OR **grid** OR **network** OR **waste** OR **sewage** OR **sewerage** OR **telecom*** OR **wireline** OR **wireless** OR **mobile** OR **pipeline***
(S3) Influential factors	**(business** OR **econom*** OR **demograph***OR **geograph*** OR **politic*** OR **environment*** OR **social** OR **technolog*** OR **stakeholder*)** AND **(variable*** OR **indicator*** OR **statistic*** OR **factor*** OR **determinant*** OR **performance** OR **data** OR **aspect*** OR **condition*** OR **barrier*** OR **facilitator*)**
(S4) Regulatory decision making	**regulat*** OR **polic*** OR **"decision making"** OR **govern*** OR **interven*** OR **authori*** OR **mandat*** OR **de?regulat*** OR **liberali*** OR **licens***

The final set of literature to address the SubQ1 is a combination of search strings from S1 and S2. A schematic search query can be represented as follows:

SubQ1: ALL ("Search string S1" AND "Search string S2")

Using a similar approach, the schematic search queries to address the SLR sub-questions and main question are

SubQ2: ALL ("Search string S1" AND "Search string S2" AND "Search string S3")

SubQ3: ALL ("Search string S1" AND "Search string S2" AND "Search string S4")

SLR MainQ: ALL ("Keywords from S1" AND "Keywords from S2" AND "Keywords from S3" AND "Keywords from S4")

3.2.4 Databases and Additional Sources

The following databases were used in the SLR: ABI/Inform, EBSCO, Scopus and Web of Science. The selection of these databases is explained by the nature of my research topic. The topic of IS has its roots in the cross-roads of technical, business and regulation areas. ABI/Inform and EBSCO are comprehensive sources for business and economic topics, whereas Scopus and Web of Science include articles covering more technical subjects.

After the intermediate results were summarised in the SLR protocol and submitted to Review Panel members, additional articles were included in the list of final literature as direct recommendations from industry and academic experts.

3.2.5 Selection Criteria

The electronic search for articles on the basis of titles resulted in a total of 2044 articles for the three sub-questions, i.e. 920 for SubQ1, 613 for SubQ2 and 511 for SubQ3. Duplicates were removed within each sub-question but not between sub-questions as one article could potentially contribute to several sub-questions at the same time. The most important criteria for onward inclusion of papers were those providing answers to the literature review's main and sub-questions (i.e. the relevance criterion), language, scientific field and type of publication. As the first step the predefined selection criteria were applied to Titles, Abstracts and Keywords of each included paper and a shortlist of these articles was created. At the next stage the quality appraisal criteria were applied to the full text of articles from this shortlist (see Table 3-4 Quality Appraisal Criteria). Table 3-3 represents a summary of the SLR selection criteria for Titles, Abstracts and Keywords.

Table 3-3 SLR Selection criteria based on Titles, Abstracts and Keywords

Criterion	Inclusion	Exclusion	Rationale
Relevance for SLR questions	Title, Abstracts and Keywords address sharing models in infrastructures (energy, transport, telecom, water, waste); discuss regulatory perspectives for infrastructure development and sharing; reviews enablers and barriers to sharing in infrastructures; compares differences and similarities between network industries.	Irrelevant studies or studies which refer only to broad general concepts of public utilities; studies on commons (fisheries, forests, rivers, etc.)	Studies address review questions and contribute to the research topic of analysing sharing methods and models in man-made infrastructures and network industries.
Language	English.	Non English.	Universal and generally accepted language of international academic community.
Scientific Field	Infrastructure development studies, regulatory and government policy science, studies on decision making.	Natural science, civil and mechanical engineering.	Research topic and review questions are positioned in these areas.
Type of Publication	Academic, policy and practitioners' papers, conference papers, theses.	General press articles, working papers, reports.	Topic is driven by practitioners, regulators and academicians; general press articles do not meet requirements of academic research; conference papers may present concepts which will be researched later; working papers turn into article after peer review.

At the initial step of selecting articles based on Titles, Abstracts and Keywords, academic, practitioners' and conference papers were considered for review. The reason for the inclusion of practitioners, regulatory and conference papers lies in the fact that traditional IS methods are substantially researched in the academic domain (e.g. unbundling, spectrum sharing), whereas new sharing forms (e.g. virtualisation in telecoms) are nascent areas. The inclusion of non-scholarly articles imposes certain quality limitations on the proposed SLR but ensures coverage of emerging academic concepts and provides unique research opportunities. Books and book chapters were excluded from the SLR as electronic databases do not provide access to these materials.

After applying selection criteria to Titles, 250 papers were shortlisted. Based on the selection criteria applied to Abstracts, this list was further reduced to 84 articles. Before conducting the quality appraisal the shortlist of 84 articles was distributed to all Review Panel members. Dr. Martin Cave suggested including the works of Inderst and Peitz (2012), Bourreau, Cambini and Hoernig (2012), and Wright and Cave (2011). Dr. Palie Smart recommended broadening the SLR with additional material on DM in a public and government sector. To address that suggestion, a separate search on DM in regulating energy, transport, telecommunication and water infrastructures was conducted; several relevant articles were identified and the works of Karvetski, Lambert and Linkov (2009), Boggia and Rocchi (2010), and Walker (2000) were included for quality appraisal. Four articles from the original list were excluded as their full texts were not available for download. Two additional Master's theses were included in the SLR from references of conference proceedings papers. As a result, the list of 88 articles was prepared for quality appraisal.

3.2.6 Quality Appraisal for Shortlisted Articles

The full texts of shortlisted articles selected on the basis of relevance criteria were further assessed in accordance with predefined quality criteria. At the stage of quality appraisal the selected articles were included in or excluded from the SLR based on their quality of contribution to the research topic. Table 3-4 represents the list of criteria with appropriate quality ranks for each article:

Table 3-4 Quality Appraisal Criteria for SLR

Quality Criteria	**Quality score** **(1 lowest to 5 highest)**
1. Is the objective of the article rightly aligned with the objectives of my SLR? Specifically, does the article address regulatory decision making in respect of IS and joint use of public facilities?	
2. Is the research question of the article clearly formulated? 3. Is it aligned with any of this SLR questions (SubQ1, SubQ2, SubQ3 or MainQ)	
4. Is the review of relevant literature presented in the article?	
5. Does the paper present a clear methodology of research, data collection, sampling and analysis?	
6. Are the findings explicitly formulated?	
7. Does the discussion answer the research question and objectives of the paper?	
8. What is the overall quality of the paper and its contribution to knowledge? 9. What is the impact factor of the Journal? 10. What is ranking of the Journal?	
Total Score (the range is from 8 to 40+)	
Was the paper selected (if total score more than 28)	
Comments	

1=completely irrelevant, 2=relevant to a limited extent, 3=acceptable but with limitations, 4=significantly relevant, 5=completely relevant

Based on the quality appraisal, 27 articles were further excluded from the scope of SLR as their overall quality mark was below the pre-agreed minimum score of 28. The list of 61 articles selected after the quality appraisal for review is presented in Appendix B. An example of the quality appraisal form and rationale for rejected articles is presented in Appendix C. The full list of rejected 27 articles is summarised in the complete version of the SLR.

3.2.7 Selected Articles and Data Extraction

The total number of articles generated for all SLR sub-questions from the keyword search was 2044. These articles were subject to stepwise screening, selection criteria applied to Titles and Abstracts, and quality appraisal. Input of Review Panel members was also considered and the final list was further broadened. Table 3-5 represents the results at each selection stage of the SLR.

Table 3-5 Number of Articles at Each Stage of the SLR

Selection Stage of SLR	**Number of articles selected**
Title and Abstract screening for	
SubQ1	920
SubQ2	613
SubQ3	511
Total for Title and Abstract screening	2,044
After applying selection criteria to Titles	250
After applying selection criteria to Abstracts	84
After Review Panel members' recommendations	90
Selected for final quality appraisal	88
After conducting quality appraisal of Full Texts	61
Total articles reviewed	**61**

The shortlisted articles were analysed with the purpose of extracting key data. The data extraction form is presented in Table 3-6.

Table 3-6 Data Extraction Form for SLR

Ref No
Citation
Title:
Author(s):
Journal/Source:
Year:
Keywords:
Study Background
Research Question / Purpose of paper:
Primary Research Focus:
Grounding Literature:
Methodology
Method:
Data Description:
Data Collection Instrument:
Sector:
Unit of Analysis:
Analytical approach:
Type of Infrastructure Sharing:
Contribution
Key findings:
Key prepositions and arguments:
Limitations and Scope for further research:
Synthesis/Key contribution to review question(s):

An example of a data extraction form for a particular article is presented in Appendix D. The full list of data extraction forms of the 61 articles is summarised in the SLR.

3.2.8 Descriptive Account of the Literature

Descriptive analysis of the final 61 SLR articles was conducted in terms of publication year, characteristics of journals, the country of origin, the key authors, the research focus and unit analysis, the sector investigated, and information on geographical locations. The complete version of the analysis with the statistics in absolute numbers and percentages is summarised in the SLR. This section contains key descriptive points of the conducted analysis.

- The overall time span comprises a 20 year period with the earliest identified article published in 1994 and the latest in 2014.
- The total number of unique sources is 43. The ranking analysis shows that the majority of journals have an impact factor of less than 1 (28 Journals) and SCImago Journal Rank (SJR) rankings less than 1 (30 Journals). Only eight “high impact” sources with scores more 2 and five “high SJR ranking” sources with scores more than 2 were identified. The impact factor is a citation system produced by Thompson Scientific's Web of Knowledge database. The SCImago Journal Rank (SJR indicator) measures the scientific influence of academic journals from two perspectives: (i) the number of citations received by a journal and (ii) the importance of the journals where such citations come from.
- The US authors contribute 30% of all articles selected for this SLR, while UK researchers contribute 25%. One explanation for these data is that a particular topic of mandatory network sharing was originated in the US and also implemented in the UK. Another explanation is that the regulatory bodies of the UK (Ofcom, Ofwat, etc.) are leading world agencies in initiating reforms in network industries. The UK reforms fertilise subsequent research and produce a body of academic studies.

- Most of the selected articles study the theoretical and practical frameworks of infrastructure unbundling and introduction of competition in former monopolistic structures. Next in frequency of occurrence are various studies on infrastructure development including concepts of IS. Cave (2010b, 2014) reviewed and further elaborated on the theory of the ladder of investments and its applicability for new infrastructure development. Hummer *et al.* (2006) developed a theory of traffic flow to analyse the use of shared paths. Bublin and Causevic (2008) and Offergelt (2011) used game theory to model the cooperative behaviour of operators in network sharing.
- Examination of methodological approaches shows that 49% of all studies used an empirical approach, 30% involved modelling and simulation approaches, 11% of studies were based on literature reviews, 8% applied theoretical frameworks, but only 2%, i.e. one study, constructed a case study. This distribution with its particular focus on countries' performance confirms that the topic of network sharing models focuses on regulatory and comparative industry effects of various IS methods.
- The data show that 11% of all articles are dedicated to the topic of Water management, 13% of articles come from the Energy sector, the majority of 59% reviews IS methods in Telecommunications, and 16% considers Transportation and Roads. The dominance of telecommunication literature confirms the most significant contribution of this sector to the research area.

3.3 Findings

This section represents the conceptual findings related to the topic of IS in Water, Energy, Telecommunication, Transport and Other infrastructure industries.

3.3.1 Water Industry

The water industry is a network industry similar to the telecommunications, electricity and gas network industries. However, unlike the electricity and energy sectors, where countries have historically exercised a unified government approach to maintaining national grids, the water industry traditionally has been fragmented. The geographical fragmentation is due to the local nature of water supplies (Foellmi and Meister, 2012) and difficulties in transporting heavy liquid substances over long distances (Sawkins, 2001), which adversely affect the quality of water (Foellmi and Meister, 2012). The value chain fragmentation is explained by various approaches in different countries to public and private ownership of water utilities and integration of water and sewerage operations (Saal *et al.*, 2013). Moreover, the European Union (EU) issued its Water Framework Directive, saying that “Water is not a commercial product like any other, rather, a heritage which must be protected, defended and treated as such” (Foellmi and Meister, 2012). These differences explain why deregulation and liberalisation processes in the water industry historically take more time and require more careful regulatory approaches (Cave, 2008; Wright and Cave, 2011).

As with other network businesses, the water industry relies on a grid infrastructure which historically was built under a regulated monopoly regime. The monopolistic nature of water utilities and regulatory requirements to introduce competition in the water industry explains why the concept of Common Carriage is viewed as an IS regulatory approach.

3.3.1.1 Common Carriage

The origin of the Common Carriage notion comes from the legal obligations of ship-owners, inn- and stable keepers in the ancient Roman Empire to provide their services to all people without discrimination (Noam, 1994). In English common law, the term “common carrier” was first witnessed in the 1300s and in the 17th Century the concept of Common Carriage was stated in the law of businesses (Mogel and Gregg, 2004). According to this law, certain occupations such as innkeepers, smiths, taverners, etc. were viewed as “common callings” and obligated to provide their services or goods to all members of the public at reasonable rates (Mogel and Gregg, 2004). Since the late 1800s, when the

Common Carriage concept was applied in the US to the railroad industry, the concept has become a traditional regulatory remedy for other network industries (Levinson, 2009).

With regard to the water industry, Sawkins (2001) analyses the Competition Act 1998 in England and Wales and defines Common Carriage as the "shared use of the supply pipes and other infrastructure of an existing statutory undertaker by a third party in order to enable the third party to provide services within the incumbent's area". Foellmi and Meister (2012) define Common Carriage as "shared use of networks, similar to telecommunication, electricity or gas: the incumbent company is required to grant its competitors access to the network, which is assumed to be an essential facility". Foellmi and Meister (2012) also provide the rationale for Common Carriage as "it would be uneconomical for a competitor to duplicate the provision of large assets, such as the pipe network". Under the Common Carriage framework, the monopolistic infrastructure provider is mandated to open its network and grant access to alternative providers to deliver water to end-users.

Developing competition is the main driving factor for the Common Carriage concept to increase the efficiency and innovation potential of water companies. Cave (2008) mentions that the Common Carriage model, along with other initiatives (e.g. introduction of an independent water procurement entity), was stated in the UK Water Supply Licensing regime in 2005 with the main goal being to develop competition in the England and Wales water sectors. As of now, the Common Carriage model is not well developed in the UK water industry and should be implemented as an additional regulatory measure after imposing economic purchasing obligations and establishing a single independent procurement entity (Wright and Cave, 2011).

Foellmi and Meister (2012) also view the efficiency aspect as an important factor for Common Carriage. They conducted a literature review on Common Carriage and summarise that Common Carriage is not the most effective tool for competition due to technical constraints, high barriers for new water providers and regulatory ambiguity. Also, such factors as the bad impact of mixed water on pipe performance, higher costs associated with pumping requirements, and worsening water quality due to long distance transportation, all impose limitations on Common Carriage implementation at a national level. Incumbents can set access prices high to prevent new competitors from entering the market, while the regulators may not have enough leverage to enforce the co-operative behaviour of the dominant players. Moreover, there is evidence of strong political opposition to introducing competition in the water industry (Foellmi and Meister, 2012).

The model of Common Carriage in the water industry is a phenomenon which is driven exclusively by policy makers and regulators. Unlike the telecommunication industry, where certain forms of IS are initiated by business, the success of implementing Common Carriage in water can be attributed to the need for effective targeted regulation. Countries and respective water industries are facing challenges of changing climates, increasing population and water consumption, rising consumer expectations of water supplies, and emerging environmental issues (Cave, 2008). These are the drivers that force regulators and water producers to increase the efficiency of water supply operations through increased competition and innovation (Wright and Cave, 2011). Common Carriage as an IS model is one remedy in a regulator's portfolio that can bring a cumulative positive effect with other regulatory measures (inset appointments, cross-border water trade, etc.) after the consistent, continuous development of competition in an unbundled water industry.

3.3.1.2 Unbundling

Unbundling in the water industry is different from local loop unbundling (LLU) in the telecommunication industry. Rather, water industry unbundling is a process of vertical disintegration of water incumbents into services and infrastructure provision. It is a process of functional separation of monopolistic entities with the aim of introducing competition to the sector (Stern, 2012). Thus, unbundling is not an IS model *per se* but a regulatory driver for high level IS agreements when separated network providers deliver infrastructure services to competitive retailers on a contract basis (Young, 2016).

3.3.2 Energy industry

Within the scope of the current SLR, the energy sector is represented by electricity and natural gas network industries. In their work Santa and Sikora (2004) compare gas and electric power industries with respect to regulation. Unlike the segmented natural gas industry, prior to liberalisation the electricity power sector was more vertically integrated (generation, transmission and retail distribution) and represented a higher degree of monopoly. Therefore, introduction of competition in the gas industry is more feasible from the regulatory point of view than in the electricity sector. The electricity industry in the form of public or private utilities is more regionally focused, whereas the natural gas industry often focuses on delivering its product on inter-regional and nationwide levels. The difference in the physical nature of gas and electricity defines the production type and network design, i.e. electricity is transmitted at the speed of light, cannot generally be stored and is generated to meet immediate demand. Higher seasonal demand fluctuations (daily or hourly demand variability in electricity, as opposed to annual seasonal variability in gas) define the business model of economic dispatch and pooling in the electric power sector (Santa and Sikora, 2004). However, as electricity and gas industries similarly represent network monopolies, the concepts of common carriage, open access, unbundling and rights-of-way are relevant for both industries from the infrastructure development perspective.

3.3.2.1 Common Carriage

As described in section 3.3.1.1, Common Carriage is a “shared use of networks, similar to telecommunication, electricity or gas” (Foellmi and Meister 2012). In the case of electricity, competitive power generation suppliers must be able to share transmission and distribution networks to deliver electricity to end-users.

Brunekreeft (1997) defines power transmission and distribution infrastructure networks as monopolies with the characteristics of essential facilities. The principle of Common Carriage applies if network providers are separated from the electricity producers and mandated by regulation to provide shared access to infrastructure to all third parties on a non-discriminatory basis. Noam (1994) describes the English common law requirement, in which under Common Carriage infrastructure, providers are "mandated the provision of service to willing customers, bringing common carriage close to a service obligation to all once it was offered to some."

The main driver for the Common Carriage framework is the need of government to regulate monopolies to maintain competition and increase welfare. In the natural gas industry, Mogel and Gregg (2004) review the evolution of Common Carriage in the US since the first effort to impose the common carrier status on interstate gas pipelines in the 1906 Interstate Commerce Act. The authors view Common Carriage as one of the regulatory tools to correct "market disorder" and "remove artificial barriers to competition in the marketplace". Mogel and Gregg (2004) also mention enablers and barriers to introducing Common Carriage. Gas consumers generally favour Common Carriage as it secures a predictable gas supply at lower prices for many industries. However, high brokerage and additional transportation costs, different levels and seasonal fluctuations in demand among different types of consumers constitute barriers to the implementation of a Common Carriage model (Hocking, 2015).

The concept of Common Carriage is closely related to the notion of Open Access to infrastructures.

3.3.2.2 Open Access

The concepts of Common Carriage and Open Access are often mixed with each other in various academic sources. Santa and Sikora (2004) in their study of open access in the electricity and natural gas industries suggest open access is "mitigating transportation market power by means of requiring open access transportation, i.e., the ability of third parties to use transportation owners' system on a non-discriminatory basis". This definition is similar to Common Carriage. On the other hand, in his work dedicated to the comparison of the common carriage model to open access in the electricity industry, Brunekreeft (1997) defines Open Access as a condition when the "infrastructure monopolist is allowed to be active on the service market". According to Brunekreeft (1997), if the Common Carriage model assumes that competitive service providers are allowed to use the infrastructure of network monopolists, the Open Access model in contrast allows incumbents to use the retail infrastructure of service competitors to reach the premises of end-users. Brunekreeft (1997) lists major factors for forward integration as double marginalisation, price discrimination, cost asymmetries and variable input proportions.

In this SLR, Open Access is assumed to be access to the final consumer, i.e. an IS concept which allows one supplier to deliver their services to the final consumer through the infrastructure of another supplier of services (Hocking, 2015).

3.3.2.3 Unbundling

Electric power and natural gas energy segments have gone through extensive liberalisation reforms in a number of nations (Newbery, 2005; Malmendier and Schendel, 2006; Growitsch and Stronzik, 2014; Barrett, 2016). The major focus of energy reforms is to increase industry transparency and efficiency through unbundling, i.e. a vertical separation of network system operations from energy production, trade, metering and sales (Lassila *et al.*, 2009). In this SLR unbundling in the energy context is not an IS method *per se*. Rather, unbundling is an organisational disintegration of networks from services (Barrett, 2016) which raises the issue of IS of newly formed entities through the Common Carriage or Open Access models.

Lassila *et al.* (2009) view four levels of unbundling in the energy sector, i.e. administrative, management, legal and ownership unbundling. Administrative unbundling assumes only separation of accounts within one organisation. Management unbundling represents further separation of network and service operations into different business units but still within one organisation. Legal unbundling requires the creation of separate legal entities within one holding company. Ownership unbundling is an outsourcing model where infrastructure and service providers are independent companies. Lassila *et al.* (2009) mention that the key drivers for unbundling are regulatory intentions to maintain competition, tightening customer demands, infrastructure owners' policies to increase efficiency of operations, business challenges to regenerate infrastructure capacity, and the need to address climate change. However, Growitsch and Stronzik (2014) argue that unbundling may lead to a decrease of operational efficiency and overall welfare, as unbundling leads to a loss of economies of scale.

3.3.2.4 Rights-of-Way

One particular type of sharing between network infrastructures and public authorities is the concept of Rights-of-Way (Mayfield, 2017). The Rights-of-Way is a permission by regional or national state authorities to a network provider to erect infrastructure on public and private land. Mogel and Gregg (2004) in their research on the Common Carriage model in the US natural gas industry, review provisions of the US Mineral Leasing Act of 1920 where "rights-of-way through public lands would be granted to natural gas pipelines by the Secretary of Interior only upon the express condition that such pipelines shall be constructed, operated and maintained as common carriers".

3.3.3 Telecommunications

The telecommunications industry is the main locomotive of the IS topic within all network industries. One explanation is that wireline telecom has the traditional characteristics of monopolistic utilities and therefore classic concepts, e.g. Common Carriage (Hazlett and Wright, 2017), Open Access, Unbundling, Rights-of-Way (Cramer, 2016), are also relevant in telecommunications. On the other hand, unlike the water and energy industries, fast grown wireless telecoms along with the development of computer technologies and Internet boom have brought a multi-dimensional variety of telecommunications infrastructure solutions. IS in telecommunications is far more complex as it deals not only with tangible assets (site and mast sharing, network sharing, local loop unbundling) but also considers intangible assets, e.g. spectrum sharing (Mustonen *et al.*, 2017), establishes new types of shared co-operation between operators, e.g. roaming, MVNO (Shin and Bartolacci, 2007; Basso and Crocioni, 2016), and creates new forms of logical networks, e.g. virtualised networks (Costa-Perez *et al.*, 2013).

Due to the diversity of particular infrastructure topics in telecommunications, existing research studies and publications on IS are fragmented with various researchers offering their own taxonomies of IS methods. Bartlett and Jackson (2002) distinguish (i) site sharing, (ii) active sharing (Node B, Transmission, Radio network controller, Core Network), (iii) Roaming and (iv) MVNO. Berkers *et al.* (2010) provide a solid comparison of various taxonomies of IS methods in wireless communications and utilise the classification approach by Forge and Blackman (2006), i.e. (i) site sharing, (ii) mast or tower sharing, (iii) Radio Access Network (RAN) sharing, (iv) Core Network sharing, and (v) roaming. A more comprehensive approach to IS taxonomy is given by Frisanco *et al.* (2008) who present a three dimensional taxonomy of IS methods differentiated by business, technology and geographic threads. The main advantage of the three dimensional classification is that it allows several IS studies to be combined into one model.

Various aspects determine IS development. Berkers *et al.* (2010) mention that the main drivers of IS are cost reductions, a potential extra revenue stream for operators, compliance with regulatory requirements, faster deployment and network coverage, and mitigation of investment risks. On the other hand, factors such as higher exposure of operators to each other’s data and operations, potential loss of competitive advantage by a dominating operator in a long run, competition with Internet providers on service delivery site and possible cooperation with competitors, all constitute barriers to IS. Chatzicharistou (2010) synthesises the various literature on IS and defines 32 drivers for IS classified by financial, regulatory, services, and network dimensions. In addition to these dimensions, Offergelt (2011) mentions reduced environmental, health and aesthetic concerns as important drivers of IS.

The following sections review IS methods in wireline and wireless telecommunications in more detail.

3.3.3.1 Mobile Network Sharing

Mobile Network Sharing (MNS) methods consist of passive and active sharing alternatives (Bartlett and Jackson, 2002; Frisanco *et al.*, 2008; Berkers *et al.*, 2010; Onishi and Tsuna, 2010). Passive IS is a business model to share passive, i.e. non-electronic elements of operators' networks (e.g. sites, masts, poles, towers, diesel generators, ventilation and air conditioning). Active IS includes sharing of active elements of operators' networks and network control, i.e. RAN sharing (Malanchini, Valentin and Aydin, 2016). To harmonise the variety of approaches and definitions of IS, the 3GPP organisation standardised network sharing solutions (Costa-Perez *et al.*, 2013).

Passive sharing does not require significant coordination between operators. Various studies on the economic effects of IS methods report positive savings effects from implementing passive IS methods. Bartlett and Jackson (2002) report that site sharing can contribute up to 16% of overall costs savings. Frisanco *et al.* (2008) analyse the effect of IS on savings of operational (OPEX) and capital (CAPEX) expenditures and report a positive effect of passive IS of 20% in OPEX savings and up to 17% in CAPEX savings. Various combinations of active IS methods can contribute up to 37% in OPEX and 40% CAPEX savings (Frisanco *et al.*, 2008; Meddour, Rasheed and Gourhant, 2011). The study by Song *et al.* (2012) quantifies the economic effect of various MNS methods on the Korean economy and concludes that the more IS methods are implemented, the more significant the economic effect.

The impact of MNS methods is determined by three major external factors, i.e. (i) size of national land area, (ii) number of mobile network operators, and (iii) pressure to reduce costs (Onishi and Tsuna, 2010). The third factor influencing IS rollout also considers the impact of increasing consumer needs and the objectives of national regulation on cost reduction pressures.

3.3.3.2 Spectrum sharing

In their work Berkers *et al.* (2010) analyse different studies on spectrum sharing and provide a definition of spectrum sharing as “the use of the same frequency band by different RANs or services, either with coordination or possibly without any coordination between the systems, with emphasis on the spectrum access schemes and methods”. They also provide a taxonomy of spectrum sharing arrangements based on coexistence (no interference and no communication between devices) and cooperation (devices communicate to avoid interference), and sharing among equals (no priority given to any device) and based on primary-secondary agreements (priority is given to primary users). The issue of spectrum sharing is emerging due to existing outdated regulatory policies on spectrum allocation (Mustonen *et al.*, 2017), exponential growth in mobile communication, converged media streaming via wireless, and the rise of cloud computing (Blackman *et al.*, 2013). The problem of spectrum congestion imposes pressure on regulators to tailor modern forms for spectrum management, e.g. light spectrum licensing, de-licensing, authorised shared access and licensed shared access, which allows the implementation of market instruments in spectrum management and technological advances, such as cognitive radio and mesh networking.

3.3.3.3 Roaming

Roaming is the most feasible and cost efficient mode of IS at the initial stages of network development for a new operator (Song *et al.*, 2012). Under roaming agreements, one operator can virtually extend its geographical coverage and enable own subscribers to use the network of another operator (Frisanco *et al.*, 2008). Roaming agreements can be national when operators share networks within one country and international between operators from different countries. Driving factors and the regulatory rationale for national and international roaming differ. Bartlett and Jackson (2002) state that "with the minimum of operator co-operation national roaming allows maximization of coverage subject to regulatory permission". Regulators often force incumbent operators into mandatory national roaming agreements with new entrants to facilitate competition (Frisanco *et al.*, 2008). The issue of international roaming is more complicated as it is driven by operators and international travellers with less influential power on roaming regulation. Since international roaming agreements are signed on a one-by-one basis, cooperation between regulatory authorities and transaction costs become complicated. The importance of regulating international roaming tariffs is witnessed in EU countries where the market for roaming services represents 4% of all mobile revenues (compared to 1-2% in other countries) (Infante and Vallejo, 2012). Aiming to decrease roaming tariffs within the EU area and facilitate market competition, the European Commission issued several recommendations to member countries to review national roaming regulations towards lowering prices for voice and data services (Falch, Henten and Tadayoni, 2009; Infante and Vallejo, 2012).

3.3.3.4 Mobile Virtual Network Operator (MVNO)

Shin and Bartolacci (2007) provide a comprehensive literature review on MVNO diffusion in the US, EU and Asian countries and compare various definitions of MVNO by the ITU, the UK regulator Ofcom, and a telecom research provider OVUM. The authors summarise that "MVNO refers to an organization that does not have an assignment of 3G spectrum, but is capable of providing public cellular services to end users by accessing radio networks of one or more 3G spectrum holders". MVNO is a type of organisation that provides voice and data services but does not have its own telecommunication network (Bartlett and Jackson, 2002; Song *et al.*, 2012). In the case of MVNO, one (hosting) operator shares its physical infrastructure with a virtual (hosted) operator by selling network capacity and services to a new entrant for resale. The network control remains under the ownership (hosting operator) of the infrastructure.

Analysing MVNO diffusion in the US, UK and selected Asian countries (Hong Kong and Singapore) Shin and Bartolacci (2007) suggest that general market conditions and telecom industry structure are the major determinants of MVNO start-ups. Average revenue per user (ARPU), number of mobile network operators, market saturation, presence and market potential of underserved user segments, and regulatory certainty, are the major factors that influence a decision to establish an MVNO. However, the business success of an MVNO is more feasible in those markets with a higher degree of horizontal integration and where clear regulation on MVNO is witnessed. Shin and Bartolacci (2007) conclude that "the MVNO is an example that is independent from its underlying infrastructure."

3.3.3.5 Network Virtualisation

Costa-Perez *et al.* (2013) view network virtualisation as one particular type of MNS method. They define network virtualisation as a combination of several virtual networks, i.e. "slices", residing on the same physical infrastructure ("network virtualization substrate"). Virtual "slices" representing different operators are isolated from each other on a logical level, customised for the distinct needs of each operator and optimised for the most effective use of shared physical infrastructure resources. Unlike Costa-Perez *et al.* (2013) who consider network virtualisation as an additional IS method to enable operators reduce OPEX and CAPEX and address a "mobile data apocalypse", Khan *et al.* (2011) view network virtualisation as a new paradigm for Next Mobile Networks (NMN) with the traffic speed of 5Gb/sec. Panchal, Yates and Buddhikot. (2013)

confirm that network virtualisation techniques generate less cost reductions as compared to conventional passive and active IS methods but are preferable for more complicated scenarios (e.g. dynamic spectrum sharing).

Zaki *et al.* (2011) summarise motivational factors to implement network virtualisation for infrastructure providers, mobile operators and end-users. Network virtualisation enables infrastructure providers to concentrate on their core competences of maintaining and increasing the efficiency of physical networks and to save on system integration functions. Existing mobile operators can significantly reduce OPEX and CAPEX, whereas new entrants can save on initial investments for network deployment. As a result, end-users benefit from the overall increased number of competitors, and the variety of new services with reasonable prices and innovation. However, even though researchers of network virtualisation underline its promising potential, this new paradigm requires additional research to address open issues (Khan *et al.*, 2011).

3.3.3.6 Network Neutrality and Open Access

This section reviews the concepts of Network Neutrality and Open Access, which are closely related and often mixed in various sources. As for Network Neutrality, Song, Zo and Ciganek*,* (2014) describe the phenomenon as "the belief that mobile operators should treat all data equally … for transparent traffic management and prohibitions against service". Wallsten and Hausladen (2009) define Network Neutrality as "another type of mandatory network sharing" which is non-discriminatory to traffic. Hogendorn (2007) provides a definition of Network Neutrality as follows: "broadband services charge consumers only once for Internet access, do not favour one content provider over another, and do not charge content providers for sending information over broadband lines to end users". Hogendorn (2007) concludes that Network Neutrality is openness to content, whereas Open Access is openness of an infrastructure owner for other operators to provide services.

As opposed to closed access, i.e. when a provider delivers a certain service (cable, phone, Internet, etc.), Open Access means only Internet connectivity through which any content can be delivered. Hogendorn (2007) claims that in the case of Open Access, a provider has an incentive to discriminate traffic in an effort to maximise profits. Thus, Open Access is an IS method which allows operators and content providers to reach end-users but does not necessarily guarantee that all traffic from all providers will be treated equally. The main driver for Open Access is regulation, which is aimed at developing competition, innovation and increasing investments in infrastructure development. Regulated pricing and types of agreements between incumbents and new entrants (*ex post* versus *ex ante*) are the main determinants of Open Access outcomes (Bourreau *et al.*, 2012; Inderst and Peitz, 2012).

The underlined debates and motivational factors for Network Neutrality and Open Access are similar, as both concepts are concerned with the risk of discrimination. However, if the Open Access debate is more focused on the development of competition and limitation of monopolies, the Network Neutrality debate also contains political aspects of content censorship and freedom of speech. This explains why the issue of Open Access is often resolved by regulators (Katz, 2017), whereas the debate over Network Neutrality is often escalated to government and parliament level (Wallsten and Hausladen, 2009; Weisman, 2015).

3.3.3.7 Common Carriage and Rights-of-Way

The concept of Common Carriage is driven by regulators and applied to wireline incumbent telecommunication companies. Former telecom monopolies were mandated by law to deliver their services to the public on a non-discriminatory basis in respect of service providers. In this SLR, the Common Carriage concept can be considered as an IS concept when users, e.g. people, companies or competitors, are mandated to share the infrastructure of an incumbent to receive services under regulated pricing. The concept of Common Carriage is closely related to Network Neutrality. In the context of telecommunications, if Network Neutrality is openness to content (Hogendorn, 2007) then Common Carriage can be considered as openness to users. Noam (1994) rightly predicted that with the development of alternative operators, e.g. Cable and Wireless, the concept of Common Carriage would erode and be replaced by "neutral interconnection", a term which later became Network Neutrality. In 2002 and 2005, the US Federal Communications Commission eliminated Common Carriage provision from the US wholesale and retail broadband services respectively (Cherry, 2008).

Noam (1994) also mentions that if a private carrier connects to a common carrier and utilises the status of the latter to deliver its own signals, then the private carrier is bound to accept common carriage obligations for the signals coming from the common carrier's network. This is the concept of Rights-of-Way, an infrastructure concept often witnessed in transportation when a private or public network (road, highway, communication grid) resides on public land. Day (2002) defines Rights-of-Way access as "the process of negotiating agreements with local governments to install and utilize fibre-optic cable or other transmission equipment on or below public streets". The concept is primarily driven by regulation, usually on the local and regional level, and often perceived by telecom operators as a barrier (Day, 2002).

3.3.3.8 Local Loop Unbundling (LLU)

As described in section 3.3.1 for the Water industry and section 3.3.2 for the Energy industry, the concept of vertical separation through organisational unbundling is also present in the Telecommunication industry. In order to introduce competition in monopolistic incumbent networks, regulators can introduce various forms of organisational unbundling, i.e. accounting, functional, legal, and ownership unbundling (Soares and Sarmento, 2012). Organisational unbundling, which is not an IS method, is often mixed with the closely related notion of LLU (Hausman and Sidak, 1999). The purpose of LLU is to provide new operators with access to the local loop of monopoly infrastructure holders to deliver services under regulated prices without building their own infrastructure (Bourreau and Doğan, 2005). By mandating LLU, regulators aim to develop competition, enabling innovation, and benefitting end-users with broader services and lower prices (Crandall *et al.*, 2013).

In terms of IS, there are three types of LLU, i.e. full unbundling, line sharing and bitstream access (Gabelmann, 2001). Under full unbundling, the incumbent loses control over its physical last mile media (e.g. copper or fibre) which is fully transferred to be under the new entrant's management. The line sharing agreement assumes that both incumbent and new entrant simultaneously deliver their services over shared communication media (e.g. voice by incumbent and Internet by new entrant). The bitstream access grants the new entrant a certain bandwidth to deliver data over last mile media, whereas the local loop remains under the incumbent's control.

The regulatory requirement to mandate LLU was intended to pursue the following benefits. Firstly, mandatory LLU was assumed to stimulate network upgrade by the incumbent. Secondly, LLU was meant to quickly allow the new entrant to establish operations without duplicating infrastructure and prevent ineffective investments. Thirdly, LLU was believed to enable innovation through increased innovation among competitors (Biggar, 2003). However, the outcomes of LLU as a way of mandatory network sharing stated in the US Telecommunication Act 1996 were questionable (Crandall, 2005) and the regime of mandatory network sharing was subsequently abandoned in the US in 2004 (Hazlett, 2006). In Europe, LLU was actively used by regulators as the tool to promote broadband penetration and an initial step for new entrants to build new, own infrastructure (Cave, 2010b, 2014).

3.3.3.9 Crowdsourced Infrastructure

An interesting IS concept of resource pooling is given by Doyle *et al.* (2014). The authors call the concept NwoB, i.e. Network Without Borders. The NwoB model assumes that a particular network is organised on demand, e.g. crowdsourced, using public or private resources. The basis for the NwoB model is the “bring your own” concept for organising infrastructures. According to Doyle *et al.* (2014), known concepts of “bringing your own technology” (BYOT), “bringing your own phone” (BYOP), and “bringing your own PC” (BYOPC) can be further developed to “bringing your own spectrum” (BYOS), “bringing your own base station” (BYOBS), “bringing your own processing power” (BYOPP), etc.

The crowdsourcing IS model is similar to the Network Virtualisation (see 3.3.3.5) concept where, on the basis of one physical infrastructure, several logical networks are organised. However, the crowdsourcing model is different as it is larger in scale, requires the coordination of numerous resource providers (Navarro *et al.*, 2016), and calls for new regulatory considerations (Doyle *et al.*, 2014).

3.3.4 Transportation

The evolution of the transportation industry from railroads to motor and air industries is a benchmarking example of infrastructure industries’ development. From the 19th century railroad companies were not just locomotives of economic development but also drivers of regulatory reforms related to governing infrastructure monopolies, imposing deregulation regimes (e.g. the US Staggers Act in 1980 and the Air Cargo Deregulation Act in 1977) and promoting liberalisation and competition. The concept of Common Carriage in relation to the infrastructure industry was firstly applied in rail transportation and later spread to other essential facilities (Cherry, 2008). Deregulation of the transportation industry was used as a blueprint for similar reforms in the energy and telecommunication network industries.

The invention of the internal combustion engine sparked the development of the motor industry, which in turn enabled extensive road and highway development. Roads became a strategic economic resource but also corridors and conduit systems for other utilities, i.e. electricity, gas, water, sewage, and telecommunications. Infrastructure sharing models are actively used in the transportation segment above and below the road surface (Marvin and Slater, 1997).

3.3.4.1 Common Carriage, Open Access and Rights-of-Way

The concept of Common Carriage in transportation is similar to those described in sections 3.3.1 for Water, 3.3.2 for Energy and 3.3.3 for Telecommunication industries. Common Carriage in transportation means the obligation of a monopolistic carrier to provide services to the public under regulated prices. Incumbents are mandated to transfer freight or passengers on a non-discriminatory basis but can charge different prices for different user categories (e.g. couch classes). It is a form of mandatory sharing of transportation facilities between a carrier and a passenger or another (private) carrier (Cherry, 2008). The concept of Common Carriage is applied not only to carriers but also physical networks. For example, toll roads in the US do not have the right to discriminate between the vehicles and their content, providing the vehicles meet safety and regulatory requirements (Levinson, 2009). By removing discriminatory barriers, the concept of Common Carriage is driven by regulators to ensure public welfare and the development of competition.

Drew (2009) analyses Open Access in the railroad industry in different countries. The key enabler of Open Access, in this context it is granting access to rail infrastructure to competitors, is a regulatory intention to introduce competition among rail carriers. Drew (2009) shows that countries express different views on the vertical separation of the rail industry and the introduction of Open Access. North America and Japan rejected the idea of Open Access, arguing that there is competition from road truck companies. Sweden, Germany and the UK implemented reforms in the railroad industry with different degrees of vertical separation and showed growth in rail traffic after liberalisation (17%, 44% and 62% respectively in the time period 1993-2005) (Drew, 2009).

As mentioned earlier, Rights-of-Way is a permission issued by government authorities, which allows network providers to reside on public land. The Rights-of-Way concept is important for the transportation industry as railways roads, bridges, turnpikes are all ground facilities which share space and land with public property. The concept of Rights-of-Way is also relevant for general public shared paths, a lane which is jointly used by pedestrians and cyclists for recreational purposes (Hummer *et al.*, 2006; Morris *et al.*, 2009; Parsons *et al.*, 2014).

3.3.4.2 Shared rail corridors

Resor, Hickey and Trb (2005) study light rail transit (LRT) systems in the US and shared-use rail corridors. Shared-use corridors are an IS method when LRT trains use the same infrastructure as heavy freight rail carriers. According to Resor *et al.* (2005) there are three types of shared-use corridors. The first type is shared track when both LRT and heavy freight train use the same track. The second type is a shared right-of-way when freight and passenger use different tracks with the distance between track centre lines of less than 25 ft (7.62 metres). The third type is shared corridor, when rail operators share a transportation corridor for parallel line routes when the distance between tracks ranges between 25 ft and 200 ft (7.62m and 61m). In addition to tracks, the shared-use corridors also include the sharing of minor facilities, e.g. crossings and movable bridges (i.e. by passengers and freight operators).

Resor *et al.* (2005) report that the major driver of shared-use corridors is a growing demand for additional transportation capacity in densely populated areas where the introduction of additional highways and roadways is not possible or economically not feasible. Shared-use corridors offer flexibility of LRT systems mixing with city traffic and carrying passengers at a relatively high speed. The issue is driven by public demand, municipal transportation regulators and rail authorities.

3.3.4.3 Underground Sharing Methods

Marvin and Slater (1997) mention several IS methods that are used in underground facilities. Service tunnels are shared spaces under the road for network elements of all utilities, i.e. gas, water, electricity, and telecoms. Service tunnels bring advantages of improved access, reduced risk of accidental impairment, improved service coordination between cable and pipe elements, improved work safety, and elimination of open pit civil works and damage to the road surface. On the other hand, while using service tunnels, difficulties arise from different layering and isolation requirements for cables and pipes, increased risk of damage for all utilities from one network element, high installation costs in busy city districts, and problems of ownership of service tunnels.

Marvin and Slater (1997) also offer a method of reusing existing or decommissioned networks. For example, new cables can be installed inside old or redundant water or gas mains. London Underground offers its network to electricity companies to lay power cables. New underground ducting networks can be installed with a certain degree of redundancy to be sold later to telecom or cable companies. Even though reusing existing networks can significantly decrease installation and maintenance costs, there are safety concerns regarding the co-existence of critical infrastructures, e.g. power and gas, electricity and water, etc. Another organisational method for underground IS is common trenching when all utilities install their network elements at the same time once a trench is opened. This method brings advantages of significant savings on civil works and reduced road and life disruption but is difficult to implement due to complicated coordination among utilities and lack of skilled multi-utility subcontractors.

3.3.5 Convergence and Superimposing with Other Utilities

In their intent to increase profits, utilities are seeking new business opportunities and possibilities to utilise their economies of scale and scope. Water utilities merge with electricity or gas utilities and enjoy savings from shared centres of competence in billing, maintenance planning, service delivery, etc. on shared infrastructures. Mergers and acquisitions concluded on national and international levels broaden market opportunities and establish quick access to essential facilities, rights-of way and new clientele. Light forms of industry diversification push energy and rail companies to install telecommunication cables over existing core infrastructures and either sell communication transport capacity or establish their own telecommunication companies (Marvin and Slater, 1997).

3.4 Discussion

The main purpose of this SLR was to identify determinants of various forms of IS in infrastructure industries, i.e. water, energy, telecommunication and transportation. A main SLR question and three sub-questions were formulated and further deconstructed into literature domains for further search. The review was primarily aimed at exposing the evolution of IS models with the focus on regulatory drivers and DM. The literature in the research domains revealed a number of IS concepts with various degrees of maturity. On the one hand, the topic of IS in monopolistic incumbents' infrastructures is well researched in the academic domain and consistent among different utilities. On the other hand, the research on IS methods in a fast growing converged industry, e.g. telecommunication, is fragmented, primarily driven by practitioners and needs further academic investigation. Telecommunication, including converged Internet and media segments, are the major drivers of IS concepts, business models and regulation. The following sections analyse SLR findings in relation to the doctoral research. Section 3.4.1 discusses the thematic findings with the objective of addressing the review questions. Section 3.4.2 presents the key points derived from the review.

3.4.1 Answer to Review Questions

Using SLR methodology, literature domains and corresponding search vehicles were determined to address the research objectives. Thematic analysis of selected articles from Section 3.3 provides findings to answer the main research question and three sub-questions.

The main literature review question is

What aspects of inter-dependent shared infrastructures and stakeholders, e.g. users, businesses and regulators, are required for the regulatory decision-making of infrastructure sharing?

The main SLR question can be answered by constructing answers to the three review sub-questions.

3.4.1.1 Addressing Sub-Question 1

The first sub-question for systematic literature review is:

"What common sharing principles and sharing models are used in different infrastructure systems, i.e. water, energy, telecommunications and transport?"

Section 3.3 presents a comprehensive discussion of IS models and principles revealed from the SLR. Table 3-7 provides a summary of IS approaches in water, energy, telecommunication and transportation.

Table 3-7 Infrastructure Sharing Models and Principles Identified in the SLR

	Water	**Energy**	**Telecoms**	**Transport**
Common Carriage	**X**	**X**	**X**	**X**
Unbundling (administrative and management)	**X**	**X**	**X**	
Open Access		**X**	**X**	**X**
Rights-of-Way		**X**	**X**	**X**
Mobile Network Sharing			**X**	
Spectrum Sharing			**X**	
Roaming			**X**	
MVNO			**X**	
Network Virtualisation			**X**	
Network Neutrality			**X**	
Local Loop unbundling			**X**	
Crowdsourced Infrastructure			**X**	
Shared rail corridors (track sharing)				**X**
Underground Sharing (service tunnels, re-using decommissioned networks)				**X**
Convergence and Superimposing with other utilities	**X**	**X**	**X**	**X**

Table 3-7 summarises only those IS methods discovered in the 61 articles. The topics of Open Access and Rights-of-way in the Water industry and Organisational Unbundling in Transport (particularly railroad) were not identified in the set of shortlisted articles.

3.4.1.2 Addressing Sub-Question 2

The second sub-question (SubQ2) is:

"What influential factors (economic, geographic, demographic, environmental, social, political, etc.) are determinants of sharing models and sharing principles in infrastructure systems?"

Table 3-8 summarises determinants (e.g. barriers, enablers, regulatory requirements, public expectations, etc.) which influence IS models in selected infrastructure industries. Table 3-8 contains only those factors which were directly identified from selected articles in relation to respective industries.

Table 3-8 Determinants of IS Models in Selected Network Industries

Determinants	Water	Energy	Telecommunications	Transportation
Economic	Need for increased efficiency; Essential facility public good: hard to replicate; Increased water consumption/ demand growth	Seasonal demand fluctuations; Essential facility: hard to duplicate; Need for increased efficiency; Growing customer demand	Need for increased efficiency; Impact on overall industry investments; More services at better prices; Increased economic surplus	Need for increased efficiency; Growing demand and infrastructure limitations
Business	Public vs. private ownership; Investment barriers for new entrants	Large consumers secure predictable prices; High brokerage and transportation costs; Need to increase capacity	Cost reduction and Extra revenue stream; Compliance with regulation; Quick market access; Less investment risks; Industry and market structure	Roads are conduits to other utilities; Cost reduction and extra revenue stream; Economies of scale and scope with other utilities
Regulatory	Introduction of competition; Enabling innovation; Sound regulatory regime; Control of mergers	Introduction of competition; Mitigating market dominance; Mitigating economic discrimination; Control of mergers	Facilitating competition and enabling innovation; Attracting investments; Control of mergers and acquisitions	Facilitating competition and enabling innovation; Attracting investments; Control of national and international mergers
Political	Opposition to water reforms; Water quality is essential	Increasing industry transparency; Legal issues on Rights-of-Way; EU: Gas is on political agenda	Need to bridge digital divide; Revenue from spectrum licensing; EU: Roaming is a political agenda; Freedom of speech and network neutrality	Roads are a country's strategic resource; Removing discriminatory barriers on transport and roads; Legal issues on Rights-of-Way
Geographic	Local nature of water supply; Difficulties in transferring liquids	Electricity is more regionally focused, Gas is nationally focused	Size of land influences network deployment	Land characteristics influence roads deployment
Demographic	Population growth; Rising consumer expectations	Urbanisation	High population density increases congestion and saturation	High population density increases road congestions
Environmental	Changing climate; Environmental concerns	Changing climate	Environmental, health and aesthetic concerns	Environmental, health and aesthetic concerns from road constructions and civil works
Social	EU: water is not a product but 'heritage'	Need to increase welfare; Energy as human right	Need to increase welfare; Expectations of connectivity for everyone and everywhere; Internet is a human right; Public expectations of lower tariffs	Need to increase welfare; Need to reduced life disruptions from road issues
Technological	Technical constraints for water transfer (due to physical nature); Network interconnection	Nature of electricity and gas defines network design; Need to upgrade networks	Faster and simpler network deployment; Various technological platforms and constraints (spectrum); Network interconnection is vital	A need to cooperate with other utilities for joint network deployments

The IS methods were also analysed against their major stakeholders. Figure 3-3 represents the key determinants of IS methods by key stakeholders, i.e. regulators, businesses and end-users.

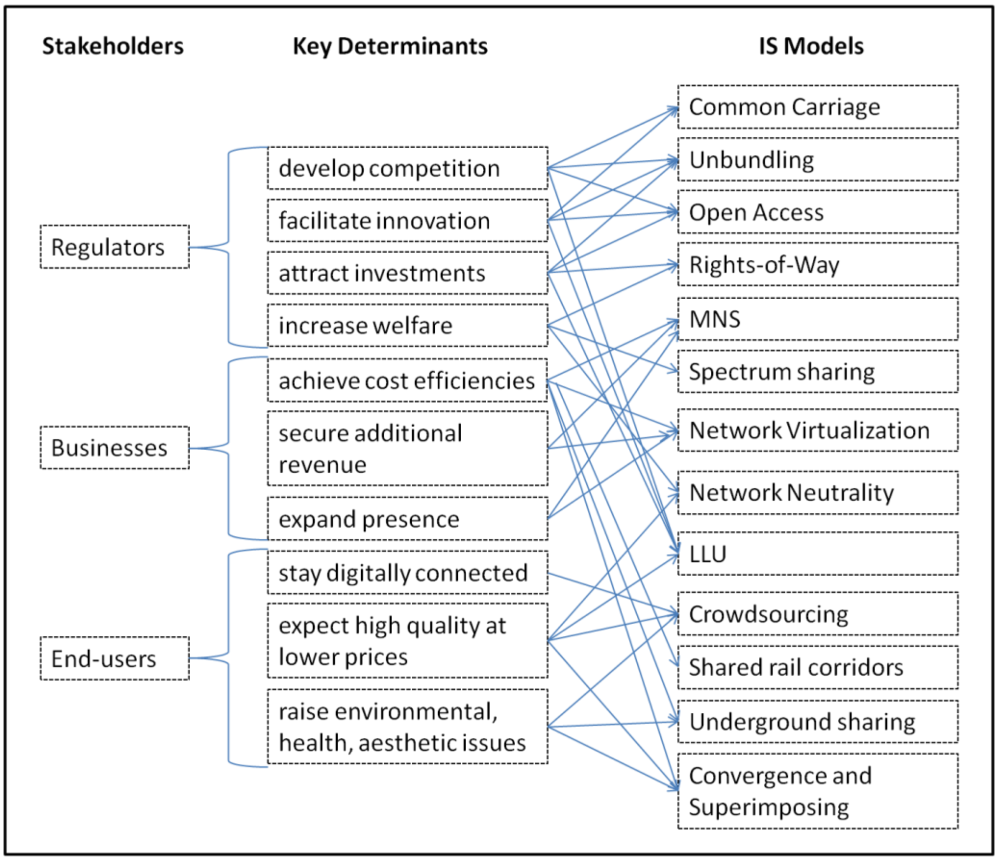

Figure 3-3 Key determinants of IS models and principles by major stakeholders

3.4.1.3 Addressing Sub-Question 3

The third sub-question (SubQ3) is:

"What common sharing principles and sharing models are relevant for regulatory decision-making in infrastructure systems?"

Findings of the review show that regulation is present in all models of infrastructure sharing, either mandatory or voluntary. One type of regulation of mandatory IS is linked to the de-monopolisation of incumbent infrastructure providers, introduction of competition and control of market power (common carriage, unbundling, open access, network neutrality). Another form of mandatory IS regulation is dealing with the coordination of scarce public resources (spectrum licensing, rights-of-way, phone number resource allocation). Regulation of voluntary IS forms is aimed at achieving economic and business objectives, such as promoting investments in infrastructure development (LLU), increasing efficiency and reducing costs (MNS, MVNO, shared corridors), improving network coverage and bridging the digital divide (roaming). Depending on the objectives of governments, certain voluntary forms of IS in one country can be mandatory in another. Regulation is closely tied to the coordination of multi-utility activities (underground sharing, convergence and superimposing infrastructures). New forms of IS (crowdsourced infrastructure, network virtualisation) require standardisation and technical regulation.

Based on the review findings for the three SLR sub-questions, the main review question can be answered:

What aspects of inter-dependent shared infrastructures and stakeholders, e.g. users, businesses and regulators, are required for the regulatory decision-making of infrastructure sharing?

Increasing a country's economic output, facilitating market efficiencies and effectiveness, addressing environmental and climate issues, empowering users with better infrastructure capacity by means of promoting competition, facilitating innovation, attracting investments in infrastructure development and coordinating scarce resources, are the major determinants of regulatory decision-making for IS.

3.4.2 Insights from the Literature

3.4.2.1 Modern "Infrastructure Sharing" is a telecom term

The findings of the review show that various sharing principles and models related to infrastructure industries exist. The term 'Infrastructure sharing' in its modern sense is naturalised in the wireless telecommunications and relates to roaming arrangements, MVNO models, spectrum sharing, sharing of mobile networks' passive facilities (sites, towers, power supply), and active elements (network access and core network sharing) (Bartlett and Jackson, 2002; Shin and Bartolacci, 2007; Bublin and Causevic, 2008; Frisanco *et al.*, 2008; Berkers *et al.*, 2010; Onishi and Tsuna, 2010; Song *et al.*, 2012; Blackman *et al.*, 2013). Academic papers on wireline telecommunications do not provide explicit sharing taxonomies but rather focus on the mandatory or voluntary nature of sharing principles (Hazlett, 2006) and scope of sharing (Hausman and Sidak, 1999; Crandall, 2005; Cave, 2010b; Crandall *et al.*, 2013). Unlike wireless telecommunications where sharing of specific network elements is clearly witnessed, in wireline telecommunication sharing concepts apply both to network elements (local loop full unbundling, shared line, bitstream access) and network as a whole (common carriage, organisational unbundling, open access, and recently network neutrality). The former concepts are relevant primarily for the telecom industry (Gabelmann, 2001; Biggar, 2003; Bourreau and Doğan, 2005; Cave, 2014) while the latter models, as well as relevance to single/all infrastructure sectors/industries, are witnessed in all utilities (Noam, 1994; Sawkins, 2001; Mogel and Gregg, 2004; Santa and Sikora, 2004; Newbery, 2005; Levinson, 2009; Foellmi and Meister, 2012).

3.4.2.2 Extant IS models reflect sector determinants and maturity

The differences and similarities in IS models in infrastructure industries are explained by different drivers and determinants. Infrastructure sharing in wireless telecommunications is primarily business driven (Berkers *et al.*, 2010; Chatzicharistou, 2010; Offergelt, 2011). Common sharing concepts in all infrastructure industries are determined by government interventions dealing with the issues of regulating monopolies, enabling competition, promoting innovation, and ensuring public good and equal access (Sawkins, 2001; Bittlingmayer and Hazlett, 2002; Day, 2002; Santa and Sikora, 2004; Hogendorn, 2007; Drew, 2009). Since traditional monopoly-like industries (railroads, pipelines, electricity grids, incumbent phone companies) have a century long history of regulation, academic studies on common network sharing concepts are mature and well established. In contrast, studies on modern IS methods related to wireless and virtualised telecommunications are driven by practitioners (Onishi and Tsuna, 2010; Khan *et al.*, 2011; Costa-Perez *et al.*, 2013; Panchal *et al.*, 2013), fragmented and narrow focused (Shin and Bartolacci, 2007; Falch *et al.*, 2009; Infante and Vallejo, 2012), and flexible in IS classification and taxonomies (Frisanco *et al.*, 2008; Meddour *et al.*, 2011).

3.4.2.3 Physical nature of good determines IS method

The variety of IS methods and their evolution is significantly determined by the physical nature of goods delivered over networks. Water, being a liquid good with low delivery speed and quality dependent on transportation distances, determines the local nature of production and supply, significance of local regulation, and modest implementation of common sharing concepts (Sawkins, 2001; Cave, 2008; Wright and Cave, 2011; Stern, 2012). Gas and Electricity networks carry single product over large distances and affect multiple regional and legal jurisdictions. Sharing concepts, such as common carriage, open access, and organisational unbundling, play a significant role in regulating energy networks (Brunekreeft, 1997; Mogel and Gregg, 2004; Pollitt, 2008; Growitsch and Stronzik, 2014). Telecommunication in its modern, converged voice and data form delivers a variety of services, requires joint use of physical resources to assuage digital hunger and enables shared virtual resources (Khan *et al.*, 2011; Zaki *et al.*, 2011; Panchal *et al.*, 2013). Transportation represented by railways and roads is often viewed as a supplier of corridors and conduits for other utilities and a basis for such sharing concepts as converged and superimposed infrastructures (Marvin and Slater, 1997).

3.4.2.4 IS drives industry integration

Convergence of network providers and sharing agreements lead to potential industry consolidation. Even though regulators force network industries to unbundle and encourage competition, IS creates vertical (value chain) and horizontal (cross-industry) integration. Newly formed entities may constitute significant market powers with monopolistic characteristics, which will again become subjects for regulatory interventions and monopoly constraints. This implies the cyclical and spiral development of certain IS concepts. Concepts such as common carriage, open access, unbundling and network neutrality remain traditional regulatory remedies in network industries. A century ago common carriage status from railway industries was imposed on the telecommunication industry (Cherry, 2008). Today, it is discussed as part of the regulatory reform in the water industry of England and Wales (Cave, 2008; Wright and Cave, 2011). Noam (1994) predicted that, with the development of alternative conduits to end-user premises and system integration, the common carriage concept in telecommunications would erode and evolve into “neural interconnection” (a concept presently known as network neutrality).

3.4.2.5 Digital demand drives IS in telecoms

The majority of SLR papers on telecommunication agree that huge digital demand is the key driving force for IS as network operators have to constantly increase infrastructure capacity under declining industry profitability (Bartlett and Jackson, 2002; Frisanco *et al.*, 2008; Khan *et al.*, 2011). However, not a single SLR paper mentioned that with the UN declaring that the Internet was a human right in 2011 (United Nations, 2011), the pressure on world governments to connect people at virtually any point of the globe will rise. This will reinforce IS concepts from the regulatory point of view. Commercial deployment of networks is economically viable in highly dense territories. In underserved areas operators have to cooperate and share facilities to meet network coverage obligations prescribed by the government in licence agreements.

3.4.2.6 Scope of SLR studies

Only one SLR paper, an academic study, was identified which was relevant to all three SLR sub-questions. Song *et al.* (2014) proposed a DM tool for policy makers, based on the MCDM method, to regulate IS methods in mobile telecommunications. The majority of SLR articles contribute to two sub-questions, mainly to types of IS and their driving factors (Frisanco *et al.*, 2008; Berkers *et al.*, 2010; Offergelt, 2011). Regulatory perspectives on sharing models are presented more in studies dedicated to unbundling monopolies. Moreover, no studies were identified where monopoly-related sharing concepts would be researched along with IS methods from mobile telecoms. Studies on DM frameworks are applied to infrastructure development in general but not to IS. This implies that a comprehensive academic field on all types of IS in infrastructure industries does not exist. Figure 3-4 represents SLR papers which are most relevant to the SLR main and sub-questions.

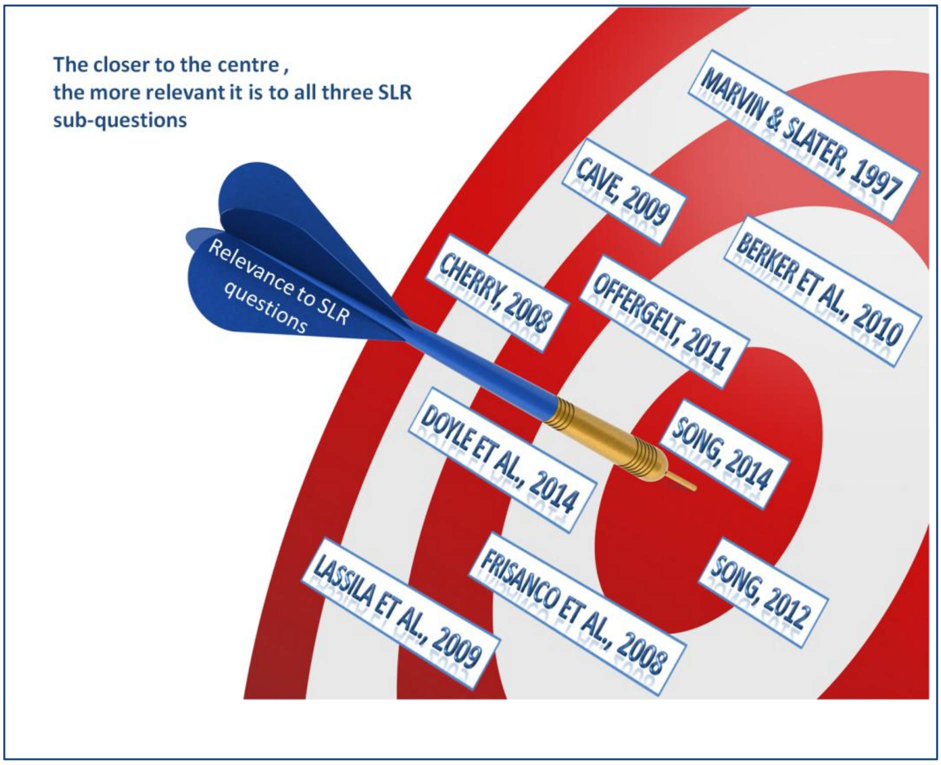

Figure 3-4 SLR papers most relevant to review questions

3.4.2.7 Key stakeholders in IS

Key stakeholders who determine IS models are regulators and businesses. By mandating IS in monopoly networks, regulators aim at introducing competition, enabling innovation and attracting investments in infrastructure development (Crandall, 2005; Malmendier and Schendel, 2006; Cave, 2010b). Voluntary sharing and MNS models have their roots in business models which pursue cost reductions, additional revenue stream, and faster network deployment (Khan *et al.*, 2011). End-users of network services are mentioned as key stakeholders with the objective of receiving a better quality service at a lower price. However, no studies in the SLR explicitly mention end-user preferences on IS. Rather, end-users are concerned about general infrastructure availability and reliability, less disruption caused by infrastructure deployment (Marvin and Slater, 1997), and health, environmental and aesthetic issues (Offergelt, 2011).

3.4.2.8 Determinants outside business vary by industry

Major external determinants of IS in telecommunication are size of land area, number of mobile network operators and pressure to reduce costs (Onishi and Tsuna, 2010). In the electricity industry, external forces affecting network development are economic supervision through regulation, ageing infrastructure, labour and material resources, climate change and reliability (Lassila *et al.*, 2009). Climate change as an external factor is also important in the water industry (Cave, 2008). In studying a particular topic of success and failures of MVNO, Shin and Bartolacci (2007) identify that industry structure, specifically a horizontal-layered structure, is the key to the successful implementation of a virtual operator.

3.4.2.9 IS does not increase investment in infrastructure

In prescribing mandatory network sharing, regulators aim at developing competition and increasing investments in new infrastructures. Studies show controversial results on the effect of mandatory sharing. Crandall (2005) states that a regime of mandatory network sharing is not welfare enhancing. In their later work Crandall *et al.* (2013) show that mandatory network sharing does not enable broadband penetration. Cave (2014) reports that unbundling of a local loop did not cause an increase in infrastructure investment. Hazlett (2006) concludes that a regime of mandatory network sharing does not meet the objectives of the US Telecommunication Act of 1996, which led to the subsequent abandonment of the Act in 2004. Voluntary MNS does not lead to increasing investment in infrastructure, as the whole objective of network operators is to reduce capital and operation expenditures related to the network. A conclusion can be derived that IS does not increase investment in infrastructure.

3.4.2.10 MCDM for infrastructure development

Findings of the SLR show that MCDM analytic tools are used in formulating regulatory policies for infrastructure development. Song *et al.* (2014) specifically use the AHP for assessing IS methods in the mobile telecommunications industry of Korea. Other studies include works by Parsons *et al.* (2014) on public Rights-of-Way based on AHP, Karvetski *et al.* (2009) on assessing options for infrastructure development based on MCDM, and Boggia and Rocchi (2010) on multipurpose water use based on Stochastic Multi-Criteria Acceptability Analysis. The proposed literature on DM suggests that MCDM methods are well suited for policy formulation as they allow the incorporation of quantitative and qualitative data while selecting alternatives and also consider group DM by various stakeholders.

3.5 Summary

The conducted review identified findings from diverse sources of academic, practical, regulatory and legislative literature, which provided a basis for answering the three sub-questions and the main question of the SLR. The study of the first review sub-question revealed that infrastructure industries, i.e. water, energy, telecommunication and transportation, have common and unique IS methods and principles. Common sharing principles are related to the monopolistic origin of utilities. Regulators debate regimes of common carriage, unbundling, open access, rights-of-way, and recently net neutrality, to prescribe mandatory network sharing to ensure market efficiencies. Unique forms of IS are witnessed in mobile telecommunications where businesses consider spectrum sharing, MNS, roaming, MVNO, and network virtualisation. Huge digital growth creates revolutionary forms of sharing paradigms, such as crowdsourced infrastructure. Infrastructure industries become inter-dependent and converge, which enables physical superimposing of utility infrastructures under, on and above the roads, corridors and ways.

Review findings related to the second sub-question identified a set of economic, business, regulatory, political, geographic, demographic, environmental, social, and technological determinants of IS models (see Table 3-8). From a regulatory perspective, the major determinants of IS are objectives to develop competition, facilitate innovation, attract investments and increase public welfare. From a business perspective, achieving cost efficiencies, securing additional revenue streams, and expanding network coverage are major drivers of sharing initiatives. End-users are demanding omnipresent digital connectivity, expecting high quality at lower prices, and becoming more concerned with the environmental, health and aesthetic issues of public infrastructures.

As for the third sub-question, the SLR analysis showed that implementation of IS methods in infrastructure industries requires various forms of regulatory prescriptions or interventions. Tight connections of utilities and regulations lie in the monopolistic nature of utilities, their influence on public good and social welfare, and economic importance for national economies. Regulators mandate network unbundling and open access to introduce competition, which is viewed as a prerequisite for innovation, market efficiency and economy drive. Infrastructure industries in general require extensive government licensing and network sharing approaches demand consents and technical approvals. New infrastructure development requires public rights-of-way. Maintaining existing infrastructures calls for coordinated policies to reduce expensive civil works and mitigate public disruption. Spectrum sharing requires government involvement in frequency coordination between military, commercial and public use. With the increasing demand for network services, the pressure for scarce natural and man-made resources will further force regulators to look for synergies between interdependent network infrastructures.

The synthesis of all SLR findings related to the three sub-questions gives the answer to the main question of the review. Regulatory decision-making of IS in inter-dependent network industries is determined by emerging needs of key stakeholders, i.e. businesses, end-users and regulators. Policy makers are concerned with increasing a country's economic output, facilitating market efficiencies and effectiveness, promoting competition and innovation, allocating scarce resources, and empowering users with better infrastructure capacity. Businesses facing declining profitability are aiming to secure additional revenue streams, decreasing capital and operation expenditures, ensuring faster network deployment and infrastructure regeneration. End-users are interested in receiving better network services at lower prices, are concerned with health, and the environmental and aesthetic aspects of modern infrastructures, and are dependent on modern networks in transforming their professional, social and personal life styles.

The findings of this SLR provide a solid foundation for the next step of the DBA studies, i.e. designing a piece of empirical research.

4 RESEARCH METHOD AND DATA DESCRIPTION

The main purpose of the research design is to model and plan an empirical research with the aim of collecting data for answering the research question, developing a clear ontological and philosophical position of the research, defining sample selection and data collection forms, planning the execution of the empirical research, analysing collected data and disseminating the results.

4.1 Initially Planned Research Methods and Scope

4.1.1 Decomposition of Previous Version of Research Question

The initial research design started with the decomposition of the research question which was formulated after the SLR phase[1]:

"What are the characteristics of a decision-making framework for regulating Infrastructure Sharing using a complex systems perspective?"

Decomposition of this version of the research question suggested that the final framework should consist of two research methods: (i) constructing an IS ecosystem of all involved stakeholders, e.g. businesses, regulators and users, with their corresponding environment using a complex systems approach, and (ii) formalising a DM aid for regulators using an MCDM technique. The former model was focused on ABM methods whereas the latter model was aimed at ANP research techniques. The final deliverable of the research process is a prototype of a decision support simulation software tool based on desktop research data.

[1] After conducting the Empirical Project the research question was altered to reflect changes derived from communication with Ofcom, the UK telecom regulator.

4.1.2 Analysing the Regulatory Field for the Research Phase

In order to formalise requirements for the proposed decision support software tool from potential beneficiaries, representatives of three NRAs were approached, i.e. from Kazakhstan, Nigeria and the UK.

The Kazakhstani regulator confirmed that the topic of IS, particularly communication tower sharing and spectrum sharing, was of current interest in terms of introducing changes in local telecom legislation. However, the Kazakhstani regulator found it difficult to come up with an issue which would be solved with the help of the proposed decision support software tool.

As for the Nigerian telecom regulator, an indirect contact was made and a verbal agreement was reached that the Nigerian NRA would consider the current research once the agenda for the potential meeting had been clearly formalised and officially presented by letter.

In February 2016, the UK telecom regulator Office of Communications (Ofcom) issued a report ‘Making communications work for everyone. Initial conclusions from the Strategic Review of Digital Communications’ (Ofcom, 2016) where the UK NRA formulated its national strategy for developing Ultrafast broadband networks. One of the objectives of the strategy is to promote infrastructure based competition and incentivise alternative operators to build their own broadband networks by forcing IS related to Duct and Pole Access (DPA) by British Telecom/Openreach (BTOR).

The current research was presented to representatives of Ofcom in May 2016 who expressed their interest in seeing a software model which would simulate development of ultrafast alternative networks in a particular geographic type of the UK with the use of two IS methods, i.e. DPA and “bitstream access”. The DPA method allows alternative operators to build their own physical infrastructure by laying fibre optic cables in BTOR ducts and poles. The “bitstream access” does not require building a physical infrastructure by an alternative operator and involves wholesale agreement with BTOR to acquire digital access to customer premises.

4.2 Actual Scope of and Methods for the Empirical Project

Based on the requirements of Ofcom representatives, the research path was designed to reflect the strategic objectives of the UK regulator and focus on two particular methods of IS: DPA and “bitstream access”.

According to Ofcom (2016), one of the strategic objectives in this area of digital communications is the large scale deployment of ultrafast networks in the UK over the next decade. To facilitate the development of new networks, Ofcom is looking at stronger regulatory interventions to provide alternative operators access to BTOR underground ducts and overhead poles. By doing so Ofcom is concerned with deliberate pricing of BTOR DPA to ensure sufficient investments from operators and protection of end-users from excessive prices for new services.

4.2.1 Model Question

The purpose of the proposed model is to explore the development of the UK’s ultrafast next generation networks from a complex system’s perspective. This design describes an agent-based model that will examine:

‘What does it take for a new operator to become competitive in the ultrafast services landscape assuming strategies are limited to building own infrastructure through BTOR duct and pole access or buying a “bitstream access” using existing BTOR networks?’

Based on a defined geographical case study, the model will answer the following questions:

- How do Ofcom interventions to regulate BTOR DPA and overall physical availability of ducts and poles influence an operator’s decision to build its own ultrafast network or buy “bitstream access” from BTOR in a particular location in the UK?

- What is the optimal price range of broadband services delivered through new ultrafast networks which would enable sufficient investments from alternative operators and generate sufficient demand by end-users?

Figure 4-1 represents three main aspects reflected in the model.

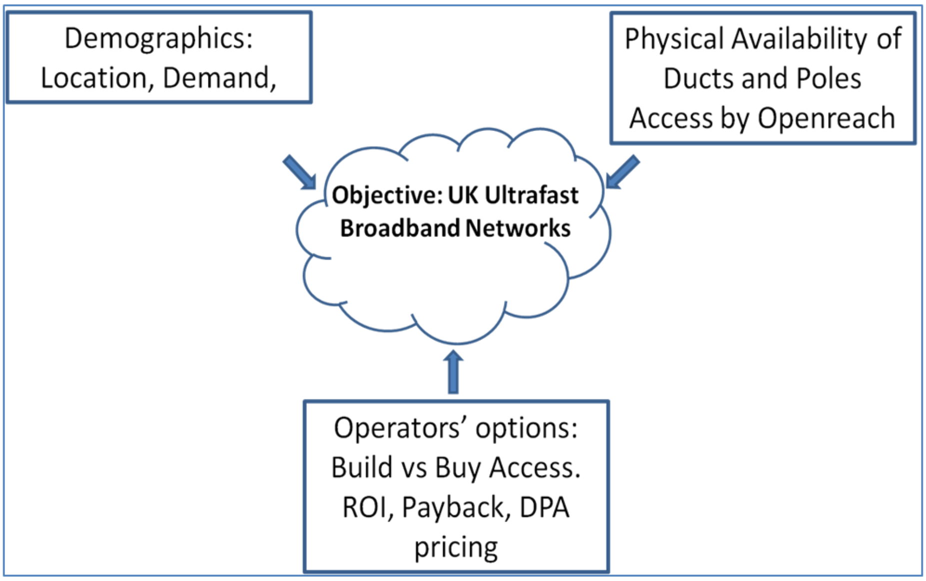

Figure 4-1 Major aspects of the model

Three main domains are reflected in the model:

I. Processes for constructing a particular UK city to reflect its demographics and demand characteristics of various groups of end-users (residential, businesses, telecom traffic).

II. Processes which affect operators' decisions to build new networks using ducts and poles or buy "bitstream access" from Openreach. The main processes are calculating trade-offs of two investment options using the classic financial models of NPV, IRR, and payback period.

III. The third set of processes is related to the physical availability of ducts and poles that enable the construction of new ultrafast networks. Based on sample data of the availability of ducts and poles in selected cities of the UK, the processes of distributing the new infrastructures are modelled.

4.2.2 Research Design

Schematic representation of the research design is exhibited in Figure 4-2.

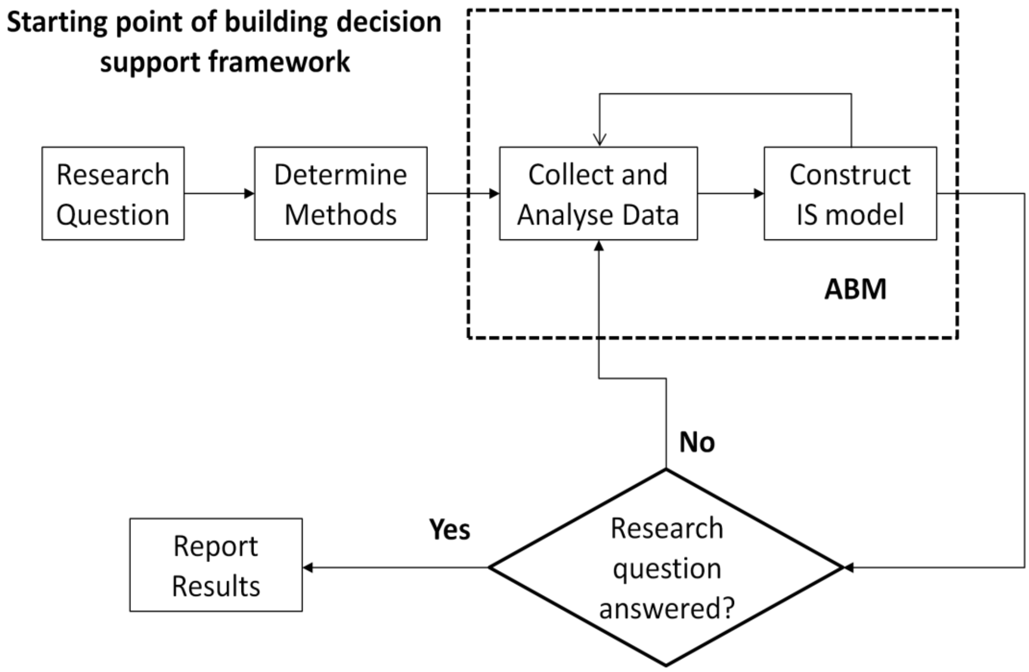

Figure 4-2 Schematic representation of research design

After iterative communications with Ofcom representatives, the scope of the research was narrowed down to constructing an IS ecosystem only. The functionality of formalising a DM aid for regulators using ANP research techniques was abandoned as the UK regulator was specifically focusing on the modelling of infrastructure scenarios with a limited number of operators in a specific market type. The regulator was more interested in seeing the complex supply and demand behaviour of all scenarios that could support the DM of the regulator to mandate IS in order to create competition, rather than analysing decisions suggested by the software tool. That is why the nature of the software model changed from ‘decision making’ to ‘decision support’ and the ANP functionality was redundant.

4.2.3 Why Agent-Based Modelling?

The ABM approach allows the simulation of individual and collective behaviour such as the market strategies of operators, e.g. BTOR and alternative infrastructure providers, types of end-user behaviour (early adopters, late majority, laggards, etc.), and characteristics of infrastructure/resource elements (duct and pole availability and continuity). The ABM approach has advantages over statistical methods of simulation as follows. ABM is preferable when there are no initially known patterns of behaviour of individual agents and an ecosystem as a whole. ABM allows capturing emergent behaviour due to interaction between agents and also modelling the outcomes of the ecosystem using the goals and objectives of its agents along with characteristics of objects. This is achieved as it allows the use of a more limited set of data concerning agents' behaviour and characteristics of objects (e.g. as in Analysys Mason ducts research (Analysys Mason, 2009) where the overall sample is less than 1% of all Openreach infrastructure).

4.2.4 Data Requirements and Data Sources

The types of data necessary for designing the decision support software tool are internal, or desk-based, research data that are used for constructing the IS model based on ABM. The majority of internal research data is readily available from the SLR.

During the design phase the research is focused on obtaining data that define the structure, functionality and outcomes of the model in accordance with Ofcom requirements. The main approach to structuring the model is to construct the demand and supply side for broadband services. The data sources used for the design are secondary data sources, which describe aspects of broadband network topologies, economics, availability of infrastructure elements and actual price characteristics from the market.

The approach and structure of the model was done using the study of Hoernig *et al.* (2010). The data on the economic framework of NGA networks were taken from Analysys Mason (2008) and CSMG (2010). The data on duct and pole availability in the UK were derived from studies by Analysys Mason (2009) and Analysys Mason (2010) which were used as empirical data from the Ofcom website. The exact data for BTOR rates for alternative operators was taken from BTOR price lists (British Telecom, 2016).

4.2.5 Processes Simulated

The main processes which are simulated in the model under different scenarios are:

i. a construction of ultrafast network by laying fibre cables through existing ducts and/or poles of BTOR or
ii. buying "bitstream access" by alternative operators from BTOR.

In the model, a new network is built when fibre cable is laid all the way from a metro node to customer premises through local exchange and street cabinet. Figure 4-3 represents the types of infrastructure links that are used to build ultrafast networks.

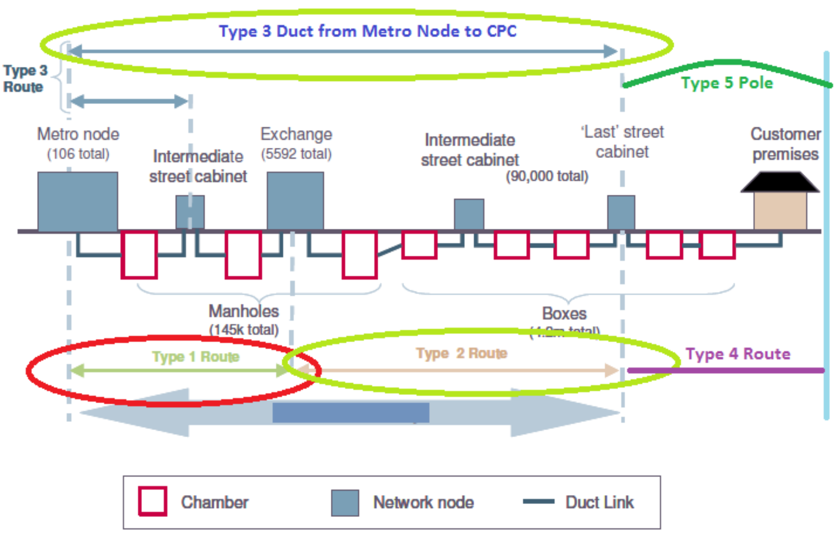

Figure 4-3 Types of ultrafast infrastructure links

In this simulation, ultrafast networks are assumed as fibre optic connections between operators' (BTOR or alternative) metro nodes (which are entry points to the main backhaul network) and customer premises. From an operator's metro node to a customer's premises a fibre cable passes the following routes (see Table 4-1):

Table 4-1 Types of Ducts and Poles Routes

Type 1	Underground duct from a Metro Node to Local Telecom Exchange
Type 2	Underground duct from a Local Telecom Exchange to a Street Cabinet (also called Primary Connection Point)
Type 3	Underground duct from a Metro Node to a Street Cabinet. It is sometimes an alternative route to Type1 + Type 2 connections
Type 4	Underground final drop from a Street Cabinet to a Customer's Premises
Type 5	Overhead final drop from a Street Cabinet to a Customer's Premises using Poles

In this simulation, a particular ultrafast network connection is complete if at least one fibre cable is inserted via existing ducts and poles or through newly built ducts and poles using the following combinations of connection types:

i. Type 1+Type 2+Type 4 (all duct connections)
ii. Type 1+Type 2+Type 5 (ducts and poles)
iii. Type 3+Type 4 (all duct connections)
iv. Type 3+Type 5 (ducts and poles)

Each combination provides a continuous path connection from a particular user to the Metro Node.

In terms of buying “bitstream access”, an alternative operator buys from BTOR a certain resource (bandwidth) under an agreed price and delivers own services using this resource. The price of the service includes price of the infrastructure resource. It is assumed in this case that BTOR offers 100% continuous availability of infrastructure resources under this scenario.

4.2.6 Design Principles and Assumptions

While developing the decision support software tool, the design followed principles and assumptions that are focused on certain selected aspects of a telecommunication market segment and purposely avoided constructing “the entire world”. The main concepts of the research design are the following:

- Since the main focus of the research is on IS, among the wide variety of IS methods in telecommunication the current research specifically focused only on DPA and “bitstream” access methods in relation to broadband networks development.
- The government sponsored Broadband Delivery UK (BDUK) plans for delivering superfast and recently ultrafast broadband are selected as the context and test ground.
- On the demand side it is assumed that Internet subscribers can be users of Regular (2Mbps), Superfast (24Mbps or more) and Ultrafast (100Mbps or more) broadband. Although the quantitative characteristics for broadband speed can vary in telecom industry benchmarking, the proposed broadband speed measures are consistent with the BDUK plans.
- User behaviour is implemented with State charts, a functionality option in simulation software that allows representing a certain status of a user. In the model it is assumed that a user can be a subscriber (be in a state) of either Regular or Superfast or Ultrafast broadband. Transitions between statuses are done from the effect of certain triggers (e.g. time, messages, actions, conditions, etc.).
- To describe various consumptions behaviour, types of users are also represented as Early Adopters (10%), Advanced Users (20%), Majority

(55%) and Conservative (15%). Sensitivity to broadband price fluctuations and probability of transitions between states for each user type are different and set in the model. Users have contracts for delivering broadband with expiration dates.

- On the supply side, it is assumed that two operators exist in the market. An incumbent operator (BTOR) which owns the existing infrastructure and an alternative operator that can consider establishing its presence by either building new or renting existing networks.
- Two approaches are available to a potential operator to deliver broadband to users, i.e. build a brand new broadband network from scratch (Greenfield scenario) or use IS (Brownfield scenarios). Within Brownfield scenarios a potential operator can consider building its own physical infrastructure on the basis of an existing network using DPA or acquiring wholesale broadband capacity from a Greenfield operator.
- Telecommunication networks consist of core networks, which connect operators to each other, and access networks, which link end-users to their immediate local operator. The scope of this model is an access network consisting of the following four cascading nodes: (1) a Metro Node, where backhaul network terminates and access network starts, (2) an Exchange Node where traffic from several districts is aggregated, (3) a Street Box node where broadband traffic is collected from customer premises, and (4) a User Node, a customer’s premises where broadband traffic terminates.
- Links between nodes are represented as containers (ducts or poles) in the model which contain fibre cables. Availability of space for fibre cables inside containers is randomised with empirical distribution functions.
- Infrastructure is built using a tree layout. Users are connected to the closest Street Box node, street boxes are connected to a closest Exchange. All exchanges are connected to the Metro Node.
- In case of the Brownfield DPA scenario, only direct continuity from the Metro Node to a User is considered without alternative (reservation) paths. In case there is no technical possibility to provide an alternative cable to a user, the user remains a subscriber of the existing Greenfield (BTOR) infrastructure.

- Users can upgrade to Superfast or Ultrafast state only if an appropriate infrastructure is in place. It is assumed that the dynamics of demand for ultrafast broadband services copy the demand patterns of superfast broadband services.
- Economic characteristics of Greenfield and Brownfield scenarios in the model are represented as capital expenditures (CAPEX) and operating expenditures (OPEX).
- The CAPEX items for the Greenfield scenario are:
  - Costs of overlaying ducts (poles) with fibre inside including installation and civil works.
  - Costs of equipment in exchanges
  - Costs of street cabinets with inside elements included
  - Costs of indoor fibre cabling at customer premises and connecting fees for each user
  - Costs of customer premises equipment (CPE)
- In the Brownfield DPA scenario it is assumed that an alternative operator builds own network and spends Capex on CPEs, equipment in exchanges, indoor cabling, and fibre cables. The difference in the Brownfield DPA scenario is that instead of building own ducts and poles, an alternative operator pays rent fees for layering own cable inside the ducts and over the poles. The same logic applies for placing own equipment inside Street Box, Exchange and Metro nodes. The alternative operator does not build nodes but rents space inside existing nodes and places own electronic equipment.
- In the case of the Brownfield "Bitstream" scenario, an alternative operator incurs costs for placing own CPE equipment for own subscribers, wholesale rent costs and costs for placing own equipment at BTOR exchanges. The "Bitstream" scenario costs are calculated for 20 years to make it comparable with CAPEX models.
- OPEX is calculated as a rate per user per year starting from the next year after the infrastructure is built in the case of Greenfield and Brownfield DPA scenarios.

4.2.7 Agent Types

Agents in the model are entities which have individual and group behaviour, pursue certain goals and objectives, and make decisions. A class of agents are operators who compete in the market delivering ultrafast broadband services. In the context of ultrafast networks, in a particular city of UK a typical set of operators consists of the incumbent BTOR, major cable provider, existing providers of Fibre-To-The premises (FTTx) technology, and new alternative operators wishing to roll out their services.

Openreach is an infrastructure arm of British Telecom. Since Openreach does not sell voice and broadband services directly to end-users, it is not considered as an operator by customers. However, Openreach is an operator for operators. In the case of incumbent telecommunication services, BT is the operator using Openreach's infrastructure. In this model BT and Openreach are treated as one operator with incumbent infrastructure and presented as BTOR.

Another group of agents are end-users who consume ultrafast broadband services. In this model types of end-users are residential users and business users. Other telecom operators being competitors on the retail broadband market can also be customers of each other. Operators use own and others' new ultrafast networks for transmitting aggregated amounts of digital traffic through their backhaul networks.

The following section describes each agent type in terms of its goals, strategies and interactions.

4.2.7.1 Type 1: Operators

Goals

Operators as business entities have common goals to maximise their economic metrics, e.g. maximise revenues, profits, product portfolio, market share, etc. In terms of their infrastructure, operators with existing networks (BTOR with copper networks, existing Cable and FTTx providers) have goals to utilise existing physical assets at their maximum and avoid expensive upgrades. New alternative operators have goals to establish a quick presence in the market by either building their own networks or renting infrastructure facilities from existing operators.

Strategy

Existing operators, i.e. BTOR, cable, FTTx providers, adopt strategies for maintaining and increasing their market positions using competitive pricing, preserving leading positions in the market, bundling broadband with other digital services, etc. BTOR is subject to regulatory compliance but has a strategy of maintaining its incumbent status using competitive or pseudo-competitive practices (for example, BTOR can exercise anti-competitive practices which are not explicitly regulated or stated in legislation).

Other operators have strategies to pursue their business objectives (aggressive growth, conservative development, niche playing, etc.) using accumulation of customer base, offering unique services and flexible pricing. New alternative operators have strategies which allow them to establish quick geographical presence in the short run and earn quick and substantial returns on their initial investment, building new digital branding, aggressive marketing, targeting specific market segments and/or specific needs, etc.

A decision by an operator to shift from service-based competition to infrastructure-based competition and thus to build its own physical network is done to maximise business objectives. This could not be demanded by regulatory objectives. In order to force a strategy to build their own networks, regulators must implement a combination of mandatory interventions and market incentives for alternative operators.

Strategy of BTOR

BTOR is an incumbent operator which provides broadband and voice services to 30 million customers in the UK. In terms of existing superfast broadband services, it has an objective to cover 95% of UK premises by the end of 2017.

Twenty five million homes and businesses are already covered by superfast services with 28,000 added each week.

In terms of ultrafast networks, BTOR has an objective to cover 10 million premises by the end of 2020. Currently, BTOR works with several service providers in conducting trials of ultrafast technology in Bradford (Fibre-to-the Premises with 1Gb/sec), rural areas of Campton and Meppershall villages in Bedfordshire, and in Haydon Wick. In Swansea BTOR plans to offer free ultrafast services to its customers for 6 months.

The rollout strategy is to use its existing infrastructure as much as possible. Fibre is laid to the closest street cabinet. New fibre cables are placed underground in ducts or on the poles. The final drop for fibre uses existing lines. In the case of a copper final drop, BTOR uses G.Fast technology.

In general, the overall roll out strategy of ultrafast networks is a planned upgrade of its existing networks. With its objective to cover 10 million premises by the end of 2020 it is assumed that BTOR will upgrade 33% of its existing clientele in the time period 2016-2020.

Strategy of cable and FTTx providers

Cable providers in the UK are Virgin Media, BT, Sky, TalkTalk, Plusnet and John Lewis. Virgin Media offers TV, broadband and phone packages and bundles while the others offer cable broadband and calls but not TV. In terms of fibre broadband, Virgin Media can offer superfast broadband services (100 MB/sec), whereas Sky, Plusnet, TalkTalk, and John Lewis offer standard broadband.

In a particular UK city all or some cable providers can be present.

As for the availability of fibre networks, BTOR and Virgin Media have the strategy of significant market presence nationwide.

Cityfibre has a strategy to cover certain UK cities with local fibre infrastructure. TalkTalk is also fragmented and present in York. The city of Hull is served by KCOM which has significant market power over BTOR.

Sky has announced its strategy not to build its own ultrafast network. Sky continues its strategy to buy infrastructure capacity from BTOR. It will continue focusing on delivering TV content and premium sport.

In general, there are two types of strategies for cable and FTTx providers in relation to ultrafast networks. Those operators that have their own physical cable and fibre infrastructure (i.e. Virgin Media, Cityfibre, TalkTalk, KCOM) will continue to gradually expand their network coverage. Virgin Media will grow nationwide. Cityfibre will use a strategy of fragmented presence. The second strategy of buying infrastructure capacity from BTOR will be undertaken by those operators that compete more on services (e.g. Sky).

In the model, a typical ecosystem of operators available in a certain UK city consists of the incumbent BTOR, Virgin Media with smaller geographical presence but the strategy of catching up with own fibre infrastructure, and two-three operators which deliver their own services through the networks of BTOR through local loop unbundling, bitstream access and line sharing.

Strategy of new alternative operators

New alternative operators in the model are those that decide to expand into ultrafast services. They are not necessarily completely new legal entities. These can be operators that are already present in the market and willing to grow.

Operators that have their own physical infrastructure (Virgin Media, Cityfibre, TalkTalk) or specialise in delivering digital content (Sky) consider strategies of expanding their geographical presence using BTOR infrastructure.

Although a combination of building own using DPA and using “bitstream” from BTOR can occur in reality, in this model a typical new operator can exercise two alternative strategies, either build its own infrastructure using DPA or deliver services while buying “bitstream access”. The decision about which strategy to implement is dependent on economic and strategic objectives.

Interaction

All agents in this model, i.e. operators and end-users, interact with and among each other.

- While competing for end-users, operators offer their services to all types of customers through advertising and direct contact. It is assumed that 80% of residential end-users are contacted via advertising and 20% by direct contact. In the case of business users, 50% are contacted via advertising and 50% by direct sales force. The differences in behaviour between residential and business users must be reflected in different state charts for each group of users. In the state chart for users, the transition from potential user of ultrafast services to consumer should be triggered by messages, either through advertising or direct contact.
- Alternative operators interact with BTOR and other incumbents when they want to use an incumbent's infrastructure to build their own network (DPA) or deliver their own services ("bitstream access").
- Operators interact with each other if one operator buys transit services from another operator. In the model, all alternative operators, i.e. cable, FTTx and new operators, negotiate with Openreach to use its infrastructure for transit services. Once a new broadband network is complete, its operator sells transit services to others.
- Agents also interact with infrastructure. Operators build and use infrastructure to deliver their digital services. End-users subscribe to these services by establishing a physical connection to the infrastructure using terminal equipment.

4.2.7.2 Type 2: End-users

Goals

End-users of ultrafast broadband networks want to receive better services at lower prices. With regard to new services, end-users are to decide if the value of ultrafast new services is worth paying a premium over existing services. In this model types of end-users are residential, business and operators' transit users.

In this model, a better service is a faster broadband. The ability of ultrafast broadband to consistently deliver promised speed characteristics defines the quality of the service. For example, a goal of a particular end-user, either residential or business, can be to shift from 38 Mb/sec to 100 Mb/sec or 200 Mb/sec to utilise more digital content.

Different groups of users will make decisions to shift to ultrafast networks under the following assumptions:

- 5% of existing broadband users are considered "bandwidth hungry" and ready to shift immediately to ultrafast network paying a premium price over the existing broadband plan.
- 15% of existing users will shift to ultrafast under premium prices over a two year period.
- 60% of existing users will shift once the price of ultrafast services drops to the price level of superfast services or lower.
- 20% of users will remain under their current tariff plans.

Strategy

The strategy of all types of end-users is reflected in their intention to maximise utilitarian value of new services at lower prices. As for residential users using ultrafast networks, the assumed strategy for 60% of them is to pay the same tariff they paid for superfast networks if the scope of services is not changed (e.g. same content but at higher speed). The rationale for this assumption is to reflect the market situation when expectations of users drive service providers to offer more services for the same price to stimulate loyalty and preserve customer base. Twenty percent of residential users are considered to be bandwidth hungry users ready to pay premium rates at the beginning (e.g. gamers). Within 3-5 years end-users are expected to pay a premium for ultrafast networks once they receive new services (3D content, augmented reality).

The adoption rate of ultrafast services can be modelled using the adoption characteristics of superfast services presented in Figure 4-4 (Analysys Mason, 2015). According to Analysys Mason (2015), superfast fixed broadband take-up was 30% in 2015 and 23.2% in 2014. Assuming that the massive roll out of ultrafast broadband started in 2017, the 30% coverage by ultrafast broadband can be achieved within 1-2 years. This projection is faster than in the case of superfast services due to several factors. Rate of adoption of ultrafast services can be higher as users are aware of superfast services. For infrastructure developers, upgrading from existing superfast to ultrafast networks can be faster than building a brand new infrastructure. Laggards of superfast services can jump directly to the ultrafast offering.

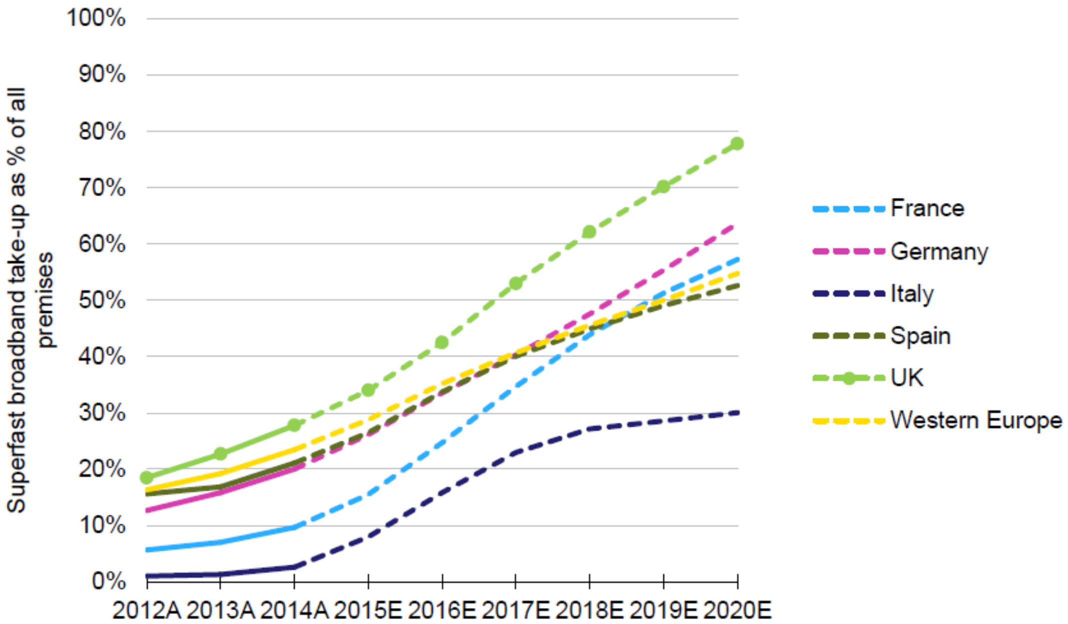

Figure 4-4 Adoption of superfast services in 5 of the EU countries (Analysys Mason, 2015)

Business users are gradually adopting new ultrafast services. Within 3-5 years after a new speed of network is available, all business users shift to new services.

Smaller operators with fragmented networks use the infrastructure of BTOR and other big operators to transit digital traffic. The contracts for transit between operators are signed separately under pre-agreed commercial agreements.

Interaction

Residential and business end-users interact with operators and among each other. To subscribe to new services or amend existing contracts, end-users communicate with operators via the Internet or directly at points of presence (e.g. retail stores). End-users also describe the services they use to each other via word of mouth or other channels, such as Facebook or email. In order for operators to sign a contract to deliver transit traffic of one operator through the infrastructure of another operator, both operators need to interact and negotiate directly.

4.2.8 Resources

Resources in this model are supplies of network infrastructure elements which are used by operators to deliver ultrafast services to end-users. In this model only the following infrastructure resources are considered

- ducts – underground channels which contain one or several fibre cables
- poles – overhead elements which deliver fibre or copper cables from a street cabinet to customer premises
- fibre cables – a medium which delivers broadband services to end-users.

4.2.8.1 Ducts and Poles

Ducts are entities with characteristics which represent availability of space for inserting new fibre cables of a certain type, e.g. one cable of 25 mm. Various types may have different space availability (Type 1 may have space for two 25 mm cables whereas the Type 2 on the same path may not have available space).

Poles are entities which have similar characteristic to ducts, e.g. available space and ability to carry fibre or copper cables of a certain type. Poles are used only from a street cabinet to customer premises.

A combination of connection types, e.g. Type 1+Type 2+Type 5, have characteristics of path continuity, i.e. an ability to form a continuous cable path from a metro node to customer premises. For example, although each Type 1 or Type 2 or Type 5 may have available space for at least one fibre cable of 25 mm, it may not be possible to form a continuous cable link because of pinch points somewhere on the route.

Duct availability on Exchange side (Type 1, Type 2, Type 3)

In the duct analysis of Type 1, Type 2 and Type 3 by Analysys Mason (2009) conducted for 11 cities in the UK the following ducts characteristics are mentioned:

- 22% of all duct ends (all Type 1-3) are full and do not have space for additional cables
- 78% of all duct ends have space for at least one 25 mm cable (14% space availability)
- 51% of all duct ends have space for three 25 mm cables (42% space availability)
- 26% of all duct ends are empty (100% space availability)

However, duct space availability does not directly correspond to space usability, i.e. an opportunity to install new cables as it can be impossible due to pinch points along the routes, congestion in chambers and reservations by Openreach. In order to analyse the risk of potential pinch points or blockages along the routes from a metro node to a street cabinet, 14 Type 3 routes were also surveyed for route continuity.

Of all 14 routes

- 46.4% of route sections had two or more empty ducts in a chamber wall.
- 17.1% of route sections had one empty duct end and one duct end that can accommodate three or more sub-ducts, or three or more duct ends that can accommodate three or more sub-ducts.
- 36.4% of route sections had conditions which are not covered by the previous two descriptions.

The route continuity suggests that usable space is not uniformly distributed along the routes and that civil works will be needed in certain sections to lay down cables.

The above mentioned data will be used for modelling a base scenario of ultrafast networks development in a generic UK region.

Duct availability on Distribution side (Type 4 and Type 5)

In the duct and pole analysis of Type 4 and Type 5 by Analysys Mason (2010) conducted for seven cities in the UK, the following duct and pole characteristics are mentioned:

- 63% of the 90 mm duct ends surveyed have at least 42% of unoccupied space
- 97% of the 50 mm duct ends surveyed have at least 42% of unoccupied space

In the analysis of spare capacity on poles, the unused capacity in the overhead infrastructure that delivers the last drop to end customers is as follows:

- 85% of the poles surveyed could accommodate at least one additional dropwire.
- 63% of the poles surveyed could accommodate at least double the amount of wires currently installed.

- 58% of dwellings are served by a pole that can accommodate at least one additional dropwire for every dwelling served by the pole without modifying the existing pole infrastructure.
- 25% of the dwellings are served by a pole that can accommodate at least two additional dropwires for all dwellings served by the pole.

DPA: Agents' interaction

In this model, if an alternative operator makes a decision to build its own network, the duct and pole availability has to be considered to simulate the process of building and costs of a newly erected infrastructure. BTOR has to provide DPA under regulated prices. New cables inserted in ducts and poles are resources which represent an output of the model, a section of the new ultrafast network. In this model it is assumed that new cables that are inserted in addition to existing cables do not alter, e.g. damage, replace, characteristics of the existing wiring.

4.2.8.2 Fibre and Copper Cables

Fibre and copper cables are resources which are used to deliver ultrafast services to customer premises. If an operator decides to build its own network, the operator is in full control of the cables (price, maintenance). If the operator decides to buy "bitstream access" from BTOR, i.e. to lease part of the capacity of existing cables, then the operator pays a certain amount for the access (which will be a premium compared to the build option) and includes this cost in the price of ultrafast services delivered to customer premises.

4.2.9 Environment and Rules

In this model, operators' decisions to build their own ultrafast networks or to buy access are assumed to be rational business decisions, i.e. decisions to utilise demand, justify investments to cover the demand, minimise costs of building infrastructure and maximise profit. Operators exist in a global environment which is represented by economic factors necessary to calculate Net Present Value (NPV), e.g. consumer demand, interest rates, etc.

The model will represent a simulation of telecommunications in a certain geographical location. Prior to running the simulation, the model user must be able to set initial conditions for the model's location. It is to be done by changing initial variables, i.e. size of population, density of population, territory occupied, number of residential users, and number of business users. Exogenous factors such as global recession are not taken into account in the model.

4.2.9.1 Emergence

The emergent behaviour in this model is observed in the global and UK trends of continuous shift to Next Generation Network broadband access. In the UK the transition from superfast to ultrafast networks has an objective to contribute to the country's overall development and boost Gross Domestic Product (GDP). On the level of a particular city, the availability of ultrafast networks decreases dependence on BTOR and increases competition, increases investments in infrastructure and overall city economy, and facilitates demand for "heavy" digital content.

4.2.9.2 Adaptation

Alternative operators in this model are able to adapt to changes while laying fibre cable in the virtual city. Prior to building its infrastructure, operators have general information on duct availability and route continuity. The exact information on whether there are additional spaces in the existing ducts or pinch points in the route appear on the spot, i.e. at the time of construction. In such situations, operators must be able to make a decision whether to use an alternative route or to build their own duct on a particular route type. This adaptation suggests the development of new skills for the operator which could lead to selling their own infrastructure leasing contracts, i.e. there is a new feedback loop which creates competition for BTOR.

4.2.9.3 Objectives

The main objective of an alternative operator is to make a rational investment decision while building a new ultrafast network. The alternative operator must undertake a strategic decision on whether a new network is economically viable. And if it is, what is the most rational way to implement it, i.e. to build its own infrastructure elements or buy access to those of BTOR?

While laying fibre cable, an objective of an operator is to optimise cable routing in terms of minimising costs and distance. Technical information on duct availability and route continuity of existing BTOR ducts and poles are not fully available. Therefore, operators have to make agile decisions using very limited knowledge.

The main objective of end-users is to receive broadband services over the new ultrafast networks at acceptable price levels.

4.2.9.4 Learning

While laying new cable and exploring actual technical availability of ducts and poles and routes continuity, operators can learn from previous experience. In the model, several iterations of the Brownfield scenario can provide estimates of DPA availability and contribute to operators' decisions on infrastructure investments.

4.2.9.5 Prediction

A prediction about whether end-users adopt new ultrafast services is based on the assumption that end-users aim at maximising utility function, i.e. satisfy certain needs or receive better services.

4.2.9.6 Sensing

Operators and end-users are sensitive to their environment. Both operators and end-users are sensitive to global economic factors which affect the income of end-users and investments of operators. End-users are also sensitive if other users have adopted new ultrafast broadband services.

4.2.9.7 Interaction

Residential users interact with each other directly as they gradually become aware of new public services via advertising and word of mouth. In relation to corporate services from the new ultrafast networks, business users gain most information from advertising and less from communicating with each other.

In order to model/introduce the effect of social networks on the adoption of ultrafast services, a Word-Of-Mouth transition will be used in the State charts for end-users. This transition indicates sharing of information among users, i.e. experienced users send messages that are received by other.

While building new networks, alternative operators interact with BTOR if they are to build infrastructure with BTOR DPA. Once services are sold using the new infrastructure, all operators interact with each other to cross sell transit services.

4.2.9.8 Stochasticity

Stochastic data on duct availability and route continuity should be entered manually at model run initiation. The demand for new services and the new services adoption rate can be parameterised at model set-up.

4.2.9.9 Collectives

End-users of ultrafast network services can be aggregated as Early Adopters, Advanced Users, Majority and Conservative. Routes are aggregated according to their types (Table 4-1). Infrastructure supply is aggregated according to simulation scenarios, i.e. Greenfield, Brownfield DPA and Bitstream.

4.2.9.10 Observation

Visual representation of the model's output can be shown in the run window with the following graphs and charts:

- Network coverage by operator (scenario).
- Infrastructure investments by network, by operator.
- Revenue generated from newly built networks by residential, business, operators' transit clients.
- Comparison of options: cost of building own infrastructure elements versus renting those of Openreach.

4.2.10 Scales

Since Ofcom sets objectives for ultrafast broadband networks for the time period of 10 years starting from 2016-2017, the simulation should run for 10 years with monthly time increments. Monthly time increments are the units of granularity taken to simulate and monitor observable dynamics of user take-up of broadband services and infrastructure development on a more detailed level.

In order to compare the "bitstream model" (OPEX model) with Greenfield and Brownfield DPA scenarios (CAPEX model), a time span of 20 years was selected in the model.

4.2.11 Initialisation

The initialisation of the model variables includes populating the virtual market with the given number of potential subscribers. All subscribers at the start-up are assumed to be users of Regular, i.e. neither Superfast nor Ultrafast, broadband. Users are also differentiated by different consumption behaviour. Also, the points for placing Street Boxes and Exchanges are defined prior to running infrastructure scenarios.

4.3 Impact Plan

The definition of the impact on economy and society is taken based on requirements by the Research Council United Kingdom (RCUK), i.e. impact aimed at improving economic performance, increasing effectiveness of public services, and enhancing quality of life and work of individuals.

Types of impact from current research is viewed through the lenses of the Economic and Social Research Council (ESRC) and differentiated as (i) instrumental, (ii) conceptual and (iii) capacity building effects. The instrumental dimension measures how research influences the provision of policy or execution of a practice, implementation of strategy or change in behaviour. The conceptual dimension is concerned with contributing to the understanding of policy or practice issues, rethinking a paradigm/debate, or questioning a notion. The capacity building thread evaluates the development of personal skills during research.

The Impact Plan (IP) considers four main areas of the research, i.e. Engagement, Dissemination, Exploitation and Evaluation of impact. The ‘Engagement’ area explains how the researcher identifies potential beneficiaries and users of the research, roles of those individuals in shaping the study, and means to approach and collect data from them. The area of ‘Dissemination’ is concerned with the approaches to distribute and popularise research ideas and outcomes among involved communities. ‘Exploitation’ is looking at converting research outcomes into practical instruments, e.g. software, tools, methodologies and guidelines, etc. ‘Evaluation of impact’ specifies and measures the range of actual/potential impacts resulting from the research. The following sections explain each of the IP areas in more detail.

4.3.1 Engagement

The SLR identified major stakeholders affected by the phenomenon of IS, e.g. regulators, businesses and users. The primary beneficiaries of this research are global telecom regulators, as current research aims to address the needs of NRAs to implement IS policies for a particular country. Various stakeholders can play different roles in the current research process. Depending on the research phase, potential users and beneficiaries can act as (i) co-producers of intellectual content and ideas, (ii) implementers of the research outcomes in the practical field, (iii) evaluators of research results, and (iv) facilitators of dissemination and exploitation of research findings.

4.3.1.1 Engagement with Regulators

To reach the targeted audience of global regulators, the engagement strategy for this research will follow three main directions, i.e. (i) focused national, (ii) regional, and (iii) global. The focused national direction is the first engagement path where the research is focused on communication with the regulators from the UK and Kazakhstan.

The regional engagement direction targets regulators from the former Soviet Union countries. The author of the research works for an incumbent operator in Kazakhstan which also presides on the Board of Operators (BO) of the Regional Commonwealth in the field of Communications (RCC) and takes part in the work of the Council of Regulating Authorities (CRA). The CRA consists of heads of telecommunication regulatory bodies from 12 member countries and four observer countries. A verbal agreement with the Chairman of the Executive Committee of the BO has been reached to introduce the current research objectives to the members of the RCC.

The global engagement direction targets individuals from the International Telecommunication Union (ITU), an information and communication arm of the UN which is in charge of standardisation of telecommunication technologies, global allocation of radio frequencies and satellite orbits, also for advising global telecom regulators by means of organising an annual Global Symposium for Regulators (GSR). A formal letter to the head of ITU, Mr. Zhao Houlin, is to be sent with the objective of introducing the research and to seek his assistance in promoting it within GSR.

4.3.1.2 Businesses

Another group of stakeholders potentially affected by this research is businesses. This group consists of various companies working in the area of developing, erecting, supplying and using telecommunication infrastructures. These are primarily mobile and wireline telecom operators but also infrastructure asset management companies (tower and mast companies, etc.), suppliers of active and passive telecommunication equipment, and other public utilities. The main sampling strategy to engage with individuals from this group is working through professional communities and organisations.

4.3.1.3 Professional community

Targeted individuals from the professional community are consultants and researchers who are involved in providing professional and academic services related to telecom infrastructures. Through personal and professional networking the author of the research has access to telecom consultants from the companies PriceWaterhouseCoopers, Deloitte, Ernst & Young, Boston Consulting Group, and McKinsey&Company. The outcomes of the research will be introduced to academicians and researchers through participation in academic conferences.

4.3.1.4 Users

The SLR findings revealed that end-users of telecommunication services are among the major determinants of modern infrastructure practices. In formulating IS policies, it is vital to receive input from the general public. The targeted audience of end-users of telecom services can be reached through social networks, user associations and user groups.

4.3.1.5 Testimonies

An effort will be made to collect three letters of testimonies from a diverse circle of evaluators, i.e. a policy maker/regulator, a telecom operator, and a representative of a user group or the general public, to obtain feedback on the DM framework for IS from different perspectives. The effort will pursue a global reach and, if possible, focus on internationally leading organisations and companies.

4.3.2 Dissemination

In order to distribute the project outcomes to a wider audience of professionals, the dissemination strategy for this research is formulated to follow three main delivery chains. The first chain is a direct communication with the end-users of this research, i.e. regulators and operators. Testing and obtaining feedback on the decision support framework from a world's leading regulator, e.g. Ofcom, raises interest in the research from a wider community.

The second delivery chain is working with the intermediaries that have the ability to spread out knowledge to a focused yet wider targeted audience. Based on the outcomes of the SLR an extended abstract on current research has been prepared with the plan to submit it to four and three star professional journals, e.g. IEEE Communications. The content of the publication will contain results of the conducted SLR and information on the further research design. The content for the publication can be summarised in a presentation and tested at practitioners' events, e.g. conferences, round tables, and seminars.

The third knowledge delivery chain is working with the social networks. The subject of IS is likely to interest specialised professional communities. Over the course of the empirical project, specialised network groups will be identified on LinkedIn, Facebook, Twitter, YouTube, etc. dedicated to the topic of telecom infrastructure development.

4.3.3 Exploitation

By sponsoring this doctoral study Kazakhtelecom is expecting to exploit outcomes of the research in its strategic and operational activities. One of the strategic objectives is to influence regulatory legislations and policies in Kazakhstan related to IS. At the moment policies on various forms of IS exist but do not provide clear rules and guides for telecom operators. The outcomes of the research can be presented to the NRA in Kazakhstan and used as the methodological basis for tailoring explicit regulatory rules and guides for IS.

The outcomes of the research can be utilised as an educational tool for academic courses or short-term professional seminars. In this case, the research outcomes can be represented as a training course with appropriate syllabus, lecture materials and software practical tools on ABM. The course can be run on behalf of a university or a consulting firm.

4.3.4 Evaluation of Impact

The main approach in evaluating the impact from the Decision Support (DS) software framework is to assess IS policies undertaken with the help of the research outcomes. The assessment can be done on different levels, i.e. organisations, economy, society and individuals, with the use of metrics appropriate for each level and group of beneficiaries.

Table 4-2 summarises the evaluation metrics on different levels and groups of beneficiaries.

Table 4-2 Metrics of Research Impact on Different Beneficiaries

Beneficiaries of the Research	**Evaluation Metrics of Impact from Implementation of the DS framework**
Organisations	For NRAs • # of countries where NRA tested the DS framework • # of countries where DS framework was implemented • organisational undertakings caused by the research (# of working groups, internal projects, new organisational units, new regulatory documents) • avoidance of financial costs (savings on consultancy and research) For Businesses • # of new geographical markets and points of presence • # of users required through DS framework implementation • # of new services delivered through IS decisions • value of additional revenue streams • avoidance of CAPEX and OPEX regarding new telecoms components (cost savings) • % performance improvement due to new equipment designed for IS as a result of DS framework implementation
Economy	• businesses more efficient due to decrease in duplication of network investment, reducing CAPEX and OPEX • improved social inclusion as business is incentivised to roll out networks in underserved areas • more businesses making use of infrastructure's improved quality of service • increased consumer choices and accessibility to telecommunications services • improved competition due to reduction in wholesale and retail

	prices • optimisation of scarce national resources, such as land or spectrum • positive environmental impacts due to more effective resource utilisation • product and technological innovation, attracting international business
Society	Metrics of Internet Penetration and Digitalisation • increased Internet coverage caused by IS and DS framework • # of new Internet users • additional volume of traffic • changes in quality of services (# of failures) • changes in pricing the telecom services • environmental, health and aesthetic gains measured by infrastructure **NOT** installed (avoided) • savings on nation's scarce sources (land, underground networks, spectrum)
Individuals	Satisfaction from Infrastructure measured by • availability, security, environmental friendliness, impact on health, aesthetic look Metrics of individual enriched lives • ability to work from home and avoided physical mobility costs and wasted time • increased use of infotainment and growth of knowledge • personal and family development potential • new career opportunities for users of the DS framework • further academic research for academicians • new skills acquired while testing the DS framework • entrepreneurial work from commercialised DS products

4.3.5 Barriers to Impact

For the successful implementation of the Impact Plan it is vital to understand the potential barriers to engagement and dissemination of project outcomes. The first group of barriers relates to insufficient preparation of research material (descriptions, presentations, letters, questionnaires, interview protocols, etc.) to be distributed to recipients. Improper preparation may lead to lost opportunities to engage with the users. The second type of barriers is related to the selection of the correct channels to approach users of the research. Certain engagements may require personal recommendations from third parties whereas for others direct contacts will be appropriate. Thirdly, the topic of IS may not be on demand by certain target groups, which may create a risk of low response rate to research inquiries and the canvassing of others to further reduce. Another potential barrier is the DS framework itself, which, on the basis of ABM, may appear too complicated for the end-users. This may lead to low dissemination rate of research outcomes. Addressing these and other latent barriers is essential for successful research impact generation.

4.3.6 Summary of Impact Plan

This section presented the Research Impact Plan for targeted audiences and explained the approaches for engagement with practice. Potential beneficiaries and users of the research, i.e. regulators, businesses, professional community and users, were identified. For each group the following were determined: contributions of roles, e.g. co-producers of intellectual content, implementers of research outcomes, evaluators of research outcomes, and facilitators of dissemination and exploitation; engagement strategies, communication channels; and means to record the output of engagement.

Three main delivery chains for dissemination strategy were formulated, i.e. direct communication with the end-users, working with the intermediaries and connecting with professional communities over social networks. Engagement and dissemination initiatives were formalised and structured on national (country focused), regional (CIS focused) and global (ITU focused) levels. The exploitation strategy to convert research findings into potential software and consultancy products, tools and instruments, guides and rules was described.

Impact evaluation of the DS framework as the final deliverable of the doctoral research on regulatory practices on IS was discussed as well as telecom operations for infrastructure development and profit maximisation, and the supply of telecom equipment and services. The section also considered the evaluation of the research impact on the economy, society and individuals. Metrics of research impact for each affected group were suggested. For successful impact generation, four groups of potential barriers to impact distribution were identified.

5 SOFTWARE MODEL: ACTUAL CONFIGURATION AND DESCRIPTION

This chapter describes the actual configuration of the decision support software tool. The information on the electronic copy of the final model deliverable is presented in 13Appendix G, ‘Electronic Version of Simulation Model’.

5.1 Demand

Demand in the model is represented by ‘Users’ agents. The common characteristics of the Type of Agent ‘User’ are described in the tab ‘User’ where the state chart of User behaviour and its general parameters are summarised. Agent type ‘User’ also inherits certain parameters of the Agent Type ‘Network Node’ for simulation purposes as the agent ‘User’ is also viewed as part (node) of the infrastructure where the network terminates. The population of agent ‘users’ and their graphical representation are given in the Tab ‘Main’ (Figure 5-1) where simulation of the whole system is taking place.

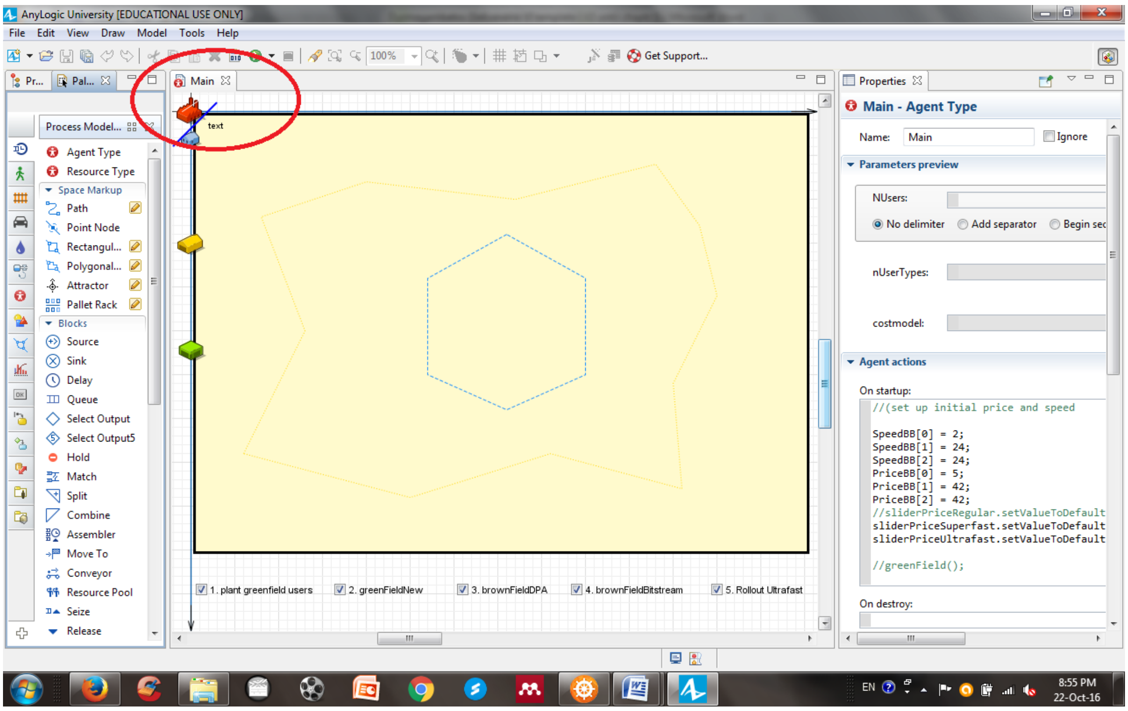

Figure 5-1 ‘Main’ Tab in AnyLogic

5.1.1 Agent User: State Chart

Behaviour of agents in AnyLogic software package is defined by state charts. An agent can be in a certain state which represents a particular status or situation. In the model, the Agent User can be a subscriber of Regular, Superfast or Ultrafast broadband. Changes between statuses are executed by transition arrows. Figure 5-2 represents the State chart of the Agent 'User'.

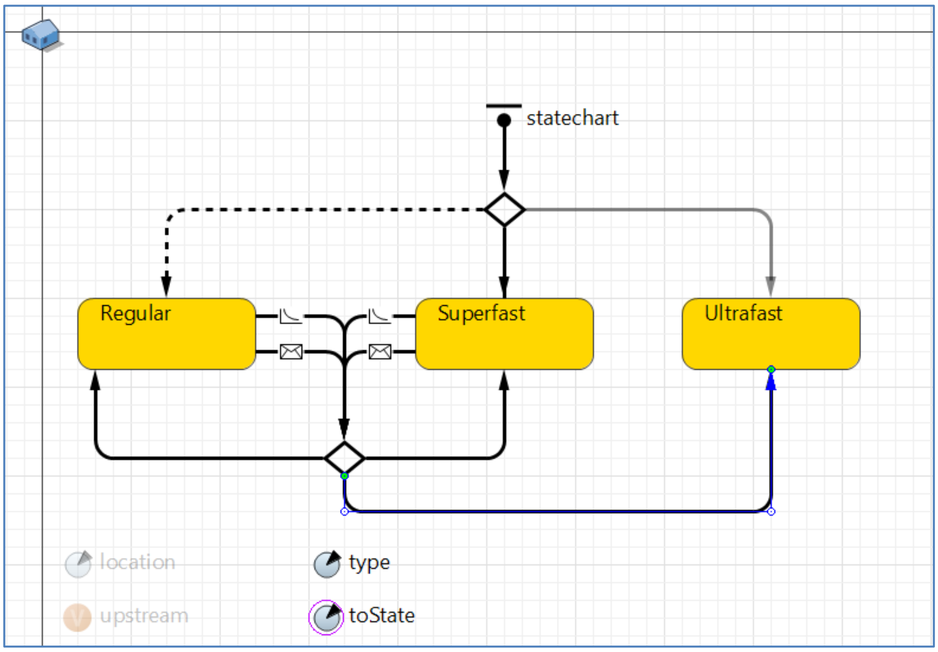

Figure 5-2 State Chart of the Agent 'User'

All User agents at the start-up of the model can be distributed between different states, meaning that users can become users of any broadband depending on their preferences and availability of appropriate infrastructure. These conditions are checked in the upper diamond block along with the expiration of the contract date.

In the software model it is assumed that all users by default become subscribers of Regular broadband, i.e. they are forced along the dashed transition line to the state "Regular". Since the major focus of this simulation is development of Superfast and Ultrafast broadband with the help of IS, the model assumes that users without Internet are not present in the market or their quantity is insignificant.

5.1.2 Transitions to Different States

Agents can move to states ‘Superfast’ or ‘Ultrafast’ in two cases, which are represented by two transition arrows, (i) a transition with the ‘envelope’ sign means that user agents receive a message that broadband infrastructure is available, and (ii) a transition with ‘exponential’ sign means that certain subgroups within the major agent group users can upgrade to Superfast or Ultrafast broadband if infrastructure is available and certain price conditions for each user subgroup are in place. For example, Early Adopters can switch to Superfast broadband if price per month for Superfast is less than 40 GBP and a probability of transition meets the condition (5-1):

$$Uniform\ P_S^{Early\ Adopter} < \frac{(0.4 * 40)}{Price_S} \quad \textbf{(5-1)}$$

where

$Uniform\ P_S^{Early\ Adopter}$	Probability of an Early Adopter agent moving to Superfast broadband follows uniform distribution
$Price_S$	Price of Superfast broadband per user per month, GBP

Table 5-1 summarises conditions of transitions from Regular to Superfast broadband for all types of users.

Table 5-1 Conditions of Transitions from Regular to Superfast Broadband

Type of User	Transition Conditions
Early Adopter	IF ($Price_S < 40GBP$) AND ($Uniform\ P_S < \frac{(0.4*40)}{Price_S}$)
Advanced User	IF ($Price_S < 35GBP$) AND ($Uniform\ P_S < \frac{(0.35*35)}{Price_S}$)
Majority	IF ($Price_S < 30GBP$) AND ($Uniform\ P_S < \frac{(0.3*30)}{Price_S}$)
Conservative	IF ($Price_S < 15GBP$) AND ($Uniform\ P_S < \frac{(0.15*15)}{Price_S}$)

where $Price_S$ Price of Superfast broadband per user per month

$Uniform\ P_S$ Probability of transition from Regular to Superfast follows uniform distribution

Similarly, the transition from Superfast to Ultrafast state for user agents can be controlled if the condition 'Ultrafast Available' is checked and price conditions for various subgroups of users are met. For example, the subgroup Majority can switch to Ultrafast broadband if price per month for Ultrafast is less than 30 GBP and a probability of transition meets the condition (5-2):

$$Uniform\ P_U^{Majority} < \frac{(0.9*30)}{Price_U} \quad \textbf{(5-2)}$$

where

$Uniform\ P_U^{Majority}$ Probability of moving to Ultrafast state for a Majority user follows uniform distribution

$Price_U$ Price of Ultrafast broadband per user per month, GBP

Table 5-2 summarises conditions of transitions from Superfast to Ultrafast broadband for all types of users.

Table 5-2 Conditions of Transitions from Superfast to Ultrafast Broadband

Type of User	Transition Conditions
Early Adopter	IF $(Price_U < 40GBP)$ AND $(Uniform\ P_U\ < \frac{(0.9*40)}{Price_U})$
Advanced User	IF $(Price_U < 35GBP)$ AND $(Uniform\ P_U\ < \frac{(0.9*35)}{Price_U})$
Majority	IF $(Price_U < 30GBP)$ AND $(Uniform\ P_U\ < \frac{(0.9*30)}{Price_U})$
Conservative	IF $(Price_U < 15GBP)$ AND $(Uniform\ P_U\ < \frac{(0.9*15)}{Price_U})$

where $Price_U$ Price of Ultrafast broadband per user per month

$Uniform\ P_U$ Probability of transition from Superfast to Ultrafast follows uniform distribution

Prices in denominators in formulae are variables which can be changed in the model with sliders to reflect an inverse relationship between the price of a service and the probability of shifting to this service.

5.1.3 List of Parameters for Agent Type 'User'

In addition to its State Chart, behaviour and actions of the Agent Type 'User' is also defined by software settings. These are parameters, variables, functions, dimensions, distributions, and option lists. Table 5-3 contains a list of settings with descriptions for Agent Type 'User'.

Table 5-3 Settings for Agent Type ‘User’

Own settings in the Tab ‘User’		
Item	**Type / Tab**	**Description**
type	Parameter / User	Differentiate user agents according to option list UserBehavior (EarlyAdopter, AdvancedUser, Majority, Conservative)
toState	Parameter /User	Integer value which represents an agent state (0 – Regular, 1 – Superfast, 2 – Ultrafast)
contractExpires	Parameter /User	Contract expiration date
cpe	Variable / User	Linked List which stores data on CPE installed by scenario (Greenfield vs. Brownfield)
indoorFibreWired	Variable / User	A Boolean indicator to check if indoor fibre cabling is completed
yearWhenConnected	Variable / User	Contains year when a user is connected to broadband
connect	Function / User	Connects CPE to a user and stores the year of connection
remove	Function / User	Removes CPE from a user
noOfCpeByOwner	Function / User	Calculates number of CPEs by Greenfield or Brownfield scenario at user location
noOfCpeByOwner	Function / User	Counts CPEs installed in or before the 'year' and owned by 'owner'
UserBehavior	Option List	Defines names of user subgroups
UserType	Dimensions	Defines dimensions for user subgroups, i.e. 1 – Regular, 2 – Superfast, 3 - Ultrafast
Settings inherited from Agent Type ‘Network Node’		
Item	**Type /Tab**	**Description**
location	Parameter / NetworkNode	Defines location of a User
upstream	Variable/ NetworkNode	A Linked List with info on containers (duct or poles) to upstream (incoming) nodes
downstream	Variable/ NetworkNode	A Linked List with info on containers (duct or poles) to downstream (outgoing) nodes
addUpstream	Function/ NetworkNode	A function that adds info on upstream containers to *upstream* Linked List
addDownstream	Function/ NetworkNode	A function that adds info on downstream containers to *downstream* Linked List

getNearestNode	Function/ NetworkNode	Gets nearest node to this node from the collection of nodes passed as an argument
getPointLocation	Function/ NetworkNode	Returns gets location of a node (User)
pathToNode	Function/ NetworkNode	Finds continuous path (in nodes) to the node provided. Only works in the upstream direction.
edgePathToNode	Function/ NetworkNode	Finds continuous path (in containers) to the node provided. Only works in the upstream direction.
Settings for Agent Type 'User' in the simulation Tab 'Main'		
userDistribution	Custom Distribution / Main	Defines custom distribution for types of User Behaviour
users [ ]	Population of agents / Main	Population of agents of the agent type 'User'. Initially empty.
userPopulation	Variable / Main	Contains total number of users
plantUsers	Function / Main	Adds users to the model. Quantity is defined in *userPopulation*
NUsers [ ]	Parameter / Main	A Hyper Array that contains number of users by their states (Regular, Superfast, Ultrafast)
nUserTypes	Parameter / Main	Defines number of User Types. Initial value = 3 (Regular, Superfast, Ultrafast)

The following chapter describes model functionality for the Supply side.

5.2 Supply

The supply side of the model is represented by Infrastructure and Operators. Infrastructure is a telecommunication network, which consists of network nodes connected by duct or pole routes. Network nodes in the model are Metro Node, an Exchange, a Street Box, and a User premises. In simulation these nodes are connected by containers which represent a duct or a pole with fibre cable inside. Depending on probability, containers have space availability for laying additional fibre cable.

Operators are agents that aim at developing a broadband network using three main scenarios:

- Greenfield scenario when an incumbent operator builds a brand new infrastructure from scratch;
- Brownfield DPA scenario when an alternative operator builds a new network on the basis of the Greenfield network using DPA;
- Brownfield 'bitstream' scenario when an alternative operator purchases (rents) wholesale fibre capacity from the Greenfield operator to deliver own content.

Figure 5-3 provides graphical representation of telecommunication network in AnyLogic.

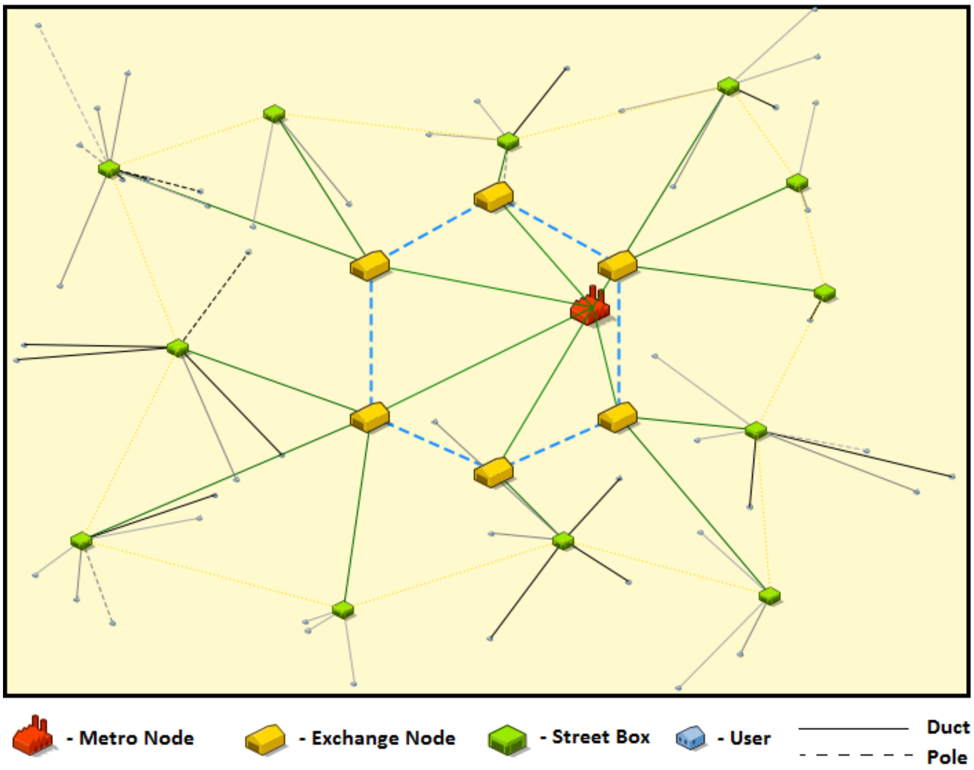

Figure 5-3 Broadband network representation in AnyLogic

Section 5.2.1 describes implemented functionality in network nodes. Section 5.2.2 provides description of links between nodes (containers with cables).

Section 5.2.3 explains representation of incumbent and alternative operators in the model.

5.2.1 Network Nodes

5.2.1.1 Agent Type 'NetworkNode'

General parameters of telecommunication nodes are configured in Agent type 'NetworkNode' from which other nodes inherit common characteristics. Table 5-4 provides description of parameters for the Agent Type 'NetworkNode'.

Table 5-4 Settings for Agent Type 'NetworkNode'

Item	**Type /Tab**	**Description**
location	Parameter / NetworkNode	Defines location of a Node
upstream	Variable/ NetworkNode	A Linked List with info on containers (duct or poles) to upstream (incoming) nodes
downstream	Variable/ NetworkNode	A Linked List with info on containers (duct or poles) to downstream (outgoing) nodes
addUpstream	Function/ NetworkNode	A function that adds info on upstream containers to *upstream* Linked List
addDownstream	Function/ NetworkNode	A function that adds info on downstream containers to *downstream* Linked List
getNearestNode	Function/ NetworkNode	Gets nearest node to this node from the collection of nodes passed as an argument
getPointLocation	Function/ NetworkNode	Returns location of a node (User)
pathToNode	Function/ NetworkNode	Finds continuous path (in nodes) to the node provided. Only works in the upstream direction.
edgePathToNode	Function/ NetworkNode	Finds continuous path (in containers) to the node provided. Only works in the upstream direction.

5.2.1.2 Agent Type 'MetroNode'

Metro Node is a point in telecommunication infrastructure where traffic from users is passed from the access network to the backhaul major network. In this simulation, the Metro Node is the starting node, which shares the general characteristics of the Agent Type 'NetworkNode'. The Metro Node is described in the Tab 'MetroNode" and represented as a single agent 'metroNode' in the presentation Tab 'Main'.

5.2.1.3 Agent Type 'ExchangeNode'

Exchange Node is a point in telecommunication infrastructure where Internet traffic from several districts is aggregated. In this simulation, the Exchange Node is the second node on the way to User premises. The Tab 'ExchangeNode' contains shared characteristics from the Agent Type 'NetworkNode', whereas population of **exchangeNodes[..]** is presented in the Tab 'Main'. The size of the population **exchangeNodes[..]** is defined by the number of nodes in the polygonal shape **'home'** (blue dashed shape in Figure 5-3) The purpose of the polygonal shape is to provide flexibility in changing the number of exchanges and their locations.

5.2.1.4 Agent Type 'StreetBox'

Street Box is a point in telecommunication infrastructure where broadband traffic is collected from customer premises. In this simulation, the 'Street Box' is the third node on the way to User premises. The Tab 'StreetBox' contains shared characteristics from the Agent Type 'NetworkNode' whereas population of **streetBoxes[..]** is presented in the Tab 'Main'. The size of the population **streetBoxes [..]** is defined by number of nodes in the polygonal shape **'streetBoxesPoints'** (yellow dotted shape in Figure 5-3). The purpose of the polygonal shape is the same as in the case of exchanges, i.e. to provide flexibility in changing the size and locations of street boxes.

5.2.1.5 Agent Type ‘User’

In this section, the agent type ‘User’ is viewed as a network node. The complete description of the ‘User’ is presented in Section 5.1 ‘Demand’.

5.2.2 Infrastructure Links

Links are infrastructure routes between network nodes. In this simulation, infrastructure links are represented as containers (either duct or pole) which carry fibre cables inside. The common characteristics of infrastructure links are described in Tab ‘NetworkEdge’, whereas individual parameters of containers and cables are presented in Tabs ‘Container’ and ‘Cable’.

5.2.2.1 Agent Type ‘NetworkEdge’

The common parameters of infrastructure links are presented for Agent Type ‘NetworkEdge’ in Table 5-5.

Table 5-5 Settings for Agent Type ‘NetworkEdge’

Item	**Type / Tab**	**Description**
Source	Parameter ‘Network Node’ / NetworkEdge	Source of a network edge (a link between nodes)
Destination	Parameter ‘Network Node’ / NetworkEdge	Destination of a network edge (a link between nodes)

5.2.2.2 Agent Type ‘Container’

Agent Type ‘Container’ can be either a duct or a pole. Since Agent ‘Container’ carries fibre cables inside, population of agent **cables[..]** of the Agent Type ‘Cable’ are defined in the Tab ‘Container’. Table 5-6 represents settings for Agent Type ‘Container’

Table 5-6 Settings for Agent Type ‘Container’

Settings inherited from Agent Type ‘NetworkEdge’		
Item	**Type / Tab**	**Description**
Source	Parameter ‘Network Node’ / NetworkEdge	Source of a network edge (a link between nodes)
Destination	Parameter ‘Network Node’ / NetworkEdge	Destination of a network edge (a link between nodes)
Own settings in the Tab ‘Container’		
Item	**Type / Tab**	**Description**
type	Parameter / Container	Differentiates between poles and ducts agents according to option list ‘ContainerType’
max_cables	Parameter / Container	Number of cables inside a container. Randomised by uniform discrete distribution (1, 2, 3)
cables[..]	Population / Container	Population of agents ‘Cable’
length	Variable / Container	Length of a container in model units
owner	Variable / Container	Type ‘Operator’, indicates owner of a cable (‘greenfield’ or ‘brownfield’)
init	Function / Container	Connects container between two nodes, measures length in model units.
add_cable	Function / Container	Adds cable inside container
noOfCablesByOwner	Function / Container	Calculates and returns number of cables by certain owner (Greenfield or Brownfield) inside a container
addSource	Function / Container	Adds Source of a container while defining continuity from a User to Metro Node
addDestination	Function / Container	Adds Destination of a container while defining continuity from a User to Metro Node
getCablesByOwner	Function / Container	Returns number of cables by a certain operator
addCableIfNotPresent	Function / Container	Adds cable by operator (e.g. ‘brownfield’) inside container only if this cable is not present

Settings for Agent Type ‘Container’ in the simulation Tab ‘Main’		
Item	**Type / Tab**	**Description**
containers[..]	Population / Main	Population of agents ‘Container’
addContainerAndCable	Function / Main	Adds container (duct or pole) between two nodes and adds cable inside belonging to either Greenfield or Brownfield operator. Changes colour of containers according to the number of cables in them.
getContainersByOwner	Function / Main	Returns number of containers by owner

5.2.2.3 Agent Type ‘Cable’

Agent Type ‘Cable’ is an agent with common characteristics of Agent Type ‘Network Edge’. Agent ‘Cables’ goes inside Container. Therefore, population of agent **cables[..]** is defined in the Tab ‘Container’. Table 5-7 represents settings for Agent Type ‘Cable’.

Table 5-7 Settings for Agent Type 'Cable'

Settings inherited from Agent Type 'NetworkEdge'		
Item	**Type / Tab**	**Description**
Source	Parameter 'Network Node' / NetworkEdge	Source of a network edge (a link between nodes)
Destination	Parameter 'Network Node' / NetworkEdge	Destination of a network edge (a link between nodes)
Own settings in the Tab 'Cable'		
Item	**Type / Tab**	**Description**
ownedBy	Parameter / Cable	Differentiates between owners of a cable (Greenfield or Brownfield)
length	Variable / Cable	Length of a cable
Settings from the Tab 'Container'		
cables[..]	Population / Container	Population of agents 'Cable'
Settings from the Tab 'Main'		
addContainerAndCable	Function / Main	Adds container (duct or pole) between two nodes and adds cable inside belonging to either Greenfield or Brownfield operator. Changes colour of containers according to the number of cables in them.
getCablesByOwner	Function / Main	Returns number of cables by owner

5.2.2.4 General Parameters for Infrastructure

Table 5-8 explains the general settings for the infrastructure defined in the Tab 'Main'.

Table 5-8 General Settings for Infrastructure

Item	Type / Tab	Description
greenField	Function / Main	Builds and calculates economics of Greenfield infrastructure
brownDPA	Function / Main	Builds and calculates economics of Brownfield DPA infrastructure
brownBitstream	Function / Main	Builds and calculates economics of Bitstream infrastructure
PriceBB[..]	Variable / Main	Array List with Prices for Regular, Superfast and Ultrafast broadband
SpeedBB[..]	Variable / Main	Array List with Speed for Regular, Superfast and Ultrafast broadband
UltrafastAvailable	Variable / Main	A Boolean check mark if Ultrafast infrastructure is available
costmodel	Parameter / Main	Initiates Java Class 'CostModel'.

5.2.3 Operators

Unlike Agent Type 'User' whose behaviour is described by State Charts, in this simulation Agent Type 'Operator' is represented as owner of the infrastructure.

5.2.3.1 Settings for Agent Type 'Operator'

The Tab 'Operator' does not contain specific settings but refers to three populations of agents in the Tab 'Main', i.e. **greenfield, brownfield, and bitstream** (Table 5-9). Each population consists of one agent.

Table 5-9 Settings for Agent Type ‘Operator’

Settings for Agent Type ‘Operator’		
Item	**Type / Tab**	**Description**
greenfield	Single agent / Main	Represents an operator who owns Greenfield infrastructure
brownfield	Single agent / Main	Represents an operator who owns Brownfield DPA infrastructure
bitstream	Single agent / Main	Represents an operator who owns Bitstream infrastructure
General Settings for ‘Operator’ and general infrastructure		
addContainerAndCable	Function / Main	Adds container (duct or pole) between two nodes and adds cable inside belonging to either Greenfield or Brownfield operator. Changes colour of containers according to the number of cables in them.
greenField	Function / Main	Builds and calculates economics of Greenfield infrastructure
brownDPA	Function / Main	Builds and calculates economics of Brownfield DPA infrastructure
brownBitstream	Function / Main	Builds and calculates economics of Bitstream infrastructure
costmodel	Parameter / Main	Initiates Java Class ‘CostModel’.
EndOfYear	Periodic Event / Main	Indicates end of year and initiates calculation of Opex for this year
Customised Java Classes for Greenfield, Brownfield DPA, and Bitstream scenarios		
CostModel	Java Class	Contains library of customised Java methods to support calculation of economic model
CPE	Java Class	Constructor initialising the fields to assign operator as an owner of CPE installed and Year of CPE installation

The Java Class ‘CostModel’ contains customised Java Methods which were developed to construct economic models for Greenfield, Brownfield and Bitstream scenarios. The following section summarises the economic framework for the software tool.

5.2.4 Economic framework

For constructing economic framework in all scenarios, “The cost of deploying fibre-based next-generation broadband infrastructure, the final report for the Broadband Stakeholder Group, Ref: 12726-371” by Analysys Mason (2008) was taken as a basis. The economic approach was also supplemented by CSMG (2010) and (Hoernig *et al.*, 2010). Based on the data from these sources, the CostModel Java Class was developed in which all economic calculations and data are summarised.

Table 5-10 provides description of data constants used in calculations of the costs for all three scenarios. Table 5-11 provides the list of methods.

Table 5-10 Constants Used in Java Class 'CostModel'

Constant	**Description**
distanceRate = 200	Adjusts model distance to "real" distance in metres for containers
ductRate = 30	Cost for new build, fibre per metre (duct, fibre, and installation costs)
fibreRateDPA = 16	Cost for Brownfield duct build, fibre per metre, GBP 8 fibre + GBP 8 installation costs
ductRent = 0.6	Cost of renting ducts, GBP per metre per year, from Openreach price list (BDUK terms)
poleRent = 0.22	Cost of renting poles, GBP 8.85 per pole divided by 40 metres, i.e. distance between poles, per single user
poleRate = 0.6	New build of poles, fibre per metre (pole, fibre, and installation costs), GBP 24 per pole divided by 40 metres, i.e. distance between poles
poleRateDPA = 16	Costs of deploying fibre in DPA, fibre per metre, GBP 8 fibre + GBP 8 installation costs
userConnectFee = 100	One time fee to connect each user inside premises
cpeRate = 80	CPE equipment costs, broadband only, no voice
indoorsFibreRate = 2000	Costs of indoor fibre cabling, one time fee, multi premises dwelling
exchangeOLT = 57600	Costs of Optical Line Termination equipment, 1 : 32 ports : 32 lines
exchangeODF = 5000	Costs of Optical Distribution Frame, 1 : 1440 fibres
exchangeFibreCost = 20	Cost per connecting each fibre cable inside an Exchange
exchangeRent = 40	Collocation rent at Exchange, per year
splitterPrice = 70	Costs of a splitter 1:8
streetBoxPrice = 13500	Costs of an empty Street Box
streetBoxRent = 20	Costs of renting space in a Street Box
opexRateGreen = 35	Annual Opex rate per User Greenfield
opexRateDPA = 25	Annual Opex rate per User Brownfield DPA
bitstreamRate = 30	Operator monthly rent for Bitstream per user

Table 5-11 Methods Used in Java Class ‘CostModel’

Method	Description
toRealDistance	Converts model distance to real distance
priceDuctPole	Returns price of a stretch of duct or pole
priceAllContainers	Calculates all container costs for Greenfield scenario
priceDuctPoleRent	Returns price of a stretch for Brownfield scenario with DPA, i.e. duct or pole is rented
priceContainersDPA	Calculates all container costs for Brownfield scenario DPA
priceAllCPE	Calculates all CPE costs
priceCpeGreen	Calculates all CPE costs for Greenfield scenario
priceCpeBrown	Calculates all costs of CPEs for Brownfield scenario DPA
priceCpe	Calculates all CPE costs for any scenario
rentAllBitstream	Calculates all monthly Bitstream rent costs for all users
priceIndoorFibre	Calculates all indoor fibre wiring costs
priceConnectUserGreen	Calculates costs of connecting users inside a premises for Greenfield
priceConnectUserBrown	Calculates costs of connecting users inside a premises for Brownfield
priceStreetCabinetDPA	Calculates costs of Street Box Equipment with DPA
priceStreetCabinet	Calculates costs of Street Box Equipment
priceExchangesGreen	Calculates costs of Exchange Equipment for Greenfield scenario
priceExchanges	Calculates costs of Exchange Equipment for Brownfield scenario
numOfSplitters	Calculates number of Splitters (1:8) ratio equipment in Street Boxes and Distribution Points combined
numOfODF	Calculates number of Optical Distribution Frames (1:1440) equipment in Exchanges
numOfOLT	Calculates number of Optical Line Terminals (1:32:32) equipment in Exchanges
priceExchangesDPA	Calculates costs of Exchange Equipment for Brownfield DPA scenario
priceExchangesBitstream	Calculates costs of Exchange Equipment for Bitstream scenario.
noOfConnectedUsers	Calculates number of connected users in any scenario (Greenfield or Brownfield)
annualOpexGreen	Calculates all Opex costs per year for Greenfield scenario
annualOpexDPA	Calculates all Opex costs per year for Brownfield scenario

5.2.4.1 Economics of Greenfield scenario

Using Java methods and constants from the Java Class ‘CostModel’ the following costs are calculated for the Greenfield scenario:

Capex

- Costs of building ducts and poles with fibre cables. Include installation and civil works
- Costs of equipment at Exchanges (Optical Distribution Frames (ODFs) and Optical Line Terminals (OLTs))
- Costs of Street Boxes with equipment installed (splitters)
- Costs of indoor fibre cabling
- Costs of CPEs including connecting fees

Opex

Opex are calculated as a rate per user per year multiplied by number of users. Annual Opex costs are incurred starting from the next year after the infrastructure is complete.

5.2.4.2 Economics of Brownfield DPA scenario

Using Java methods and constants from the Java Class ‘CostModel’ the following costs are calculated for the Brownfield DPA scenario:

Capex

- Costs of renting ducts and poles from incumbent and costs of laying new fibre cables where possible. Include installation and civil works
- Costs of renting place at Exchanges with equipment installed (ODFs and OLTs)
- Costs of renting place at Street Boxes with equipment installed (splitters)
- Costs of indoor fibre cabling
- Costs of CPEs including connecting fees

Opex

Opex are calculated as a rate per user per year multiplied by number of users. Annual Opex costs are incurred starting from the next year after the infrastructure is complete.

5.2.4.3 Economics of Bitstream scenario

Using Java methods and constants from the Java Class ‘CostModel’ the following costs are calculated for the Bitstream scenario:

- Costs of CPEs installed at customer premises.
- Costs of Equipment installed at Exchange of an incumbent operator with rent costs.
- Costs of renting fibre cable to customers’ premises (wholesale purchase from incumbent) calculated for 20 years. This model time of 20 years is selected as this span corresponds to an average life time of fibre and corresponding electronic equipment installed in network nodes. This is also selected to conduct a relative analysis of CAPEX and OPEX infrastructure scenarios.

5.3 Outcomes: Visualisation

The model outcomes are available in two forms. The first form is a graphical representation in the presentation window. In the software prototype, the following graphics are available:

- Number of users of Regular broadband
- Number of users of Superfast broadband
- Number of users of Regular broadband
- Total number of users in all states
- Broadband speed
- Capex items for Container costs
- Capex items for CPE and Fibre Cabling

Figure 5-4 provides an example of the visual representation of model outcomes where changes in user dynamics are shown on three graphs, along with the infrastructure built by the model. Figure 5-5 demonstrates the dynamics of users in different states and infrastructure Capex and Opex costs over time.

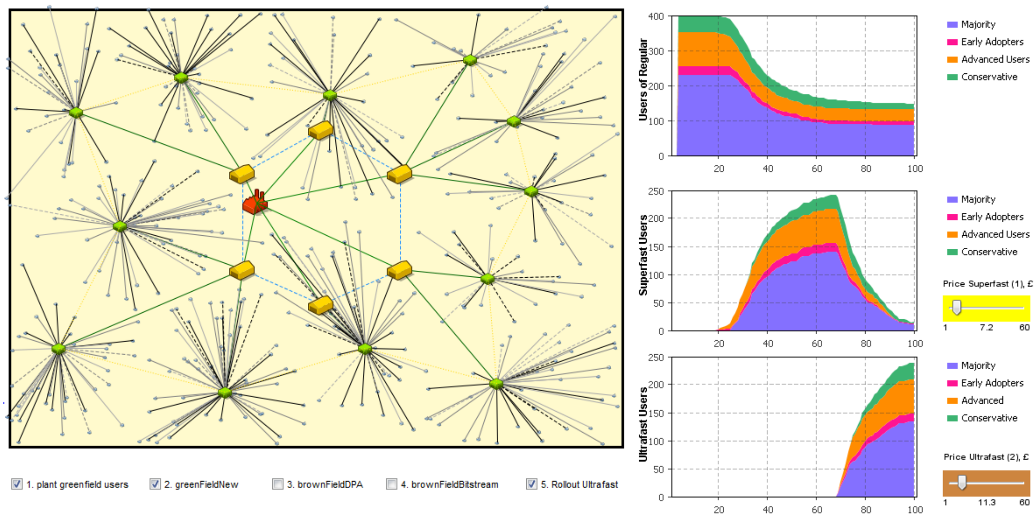

Figure 5-4 Model representation: infrastructure and user dynamics

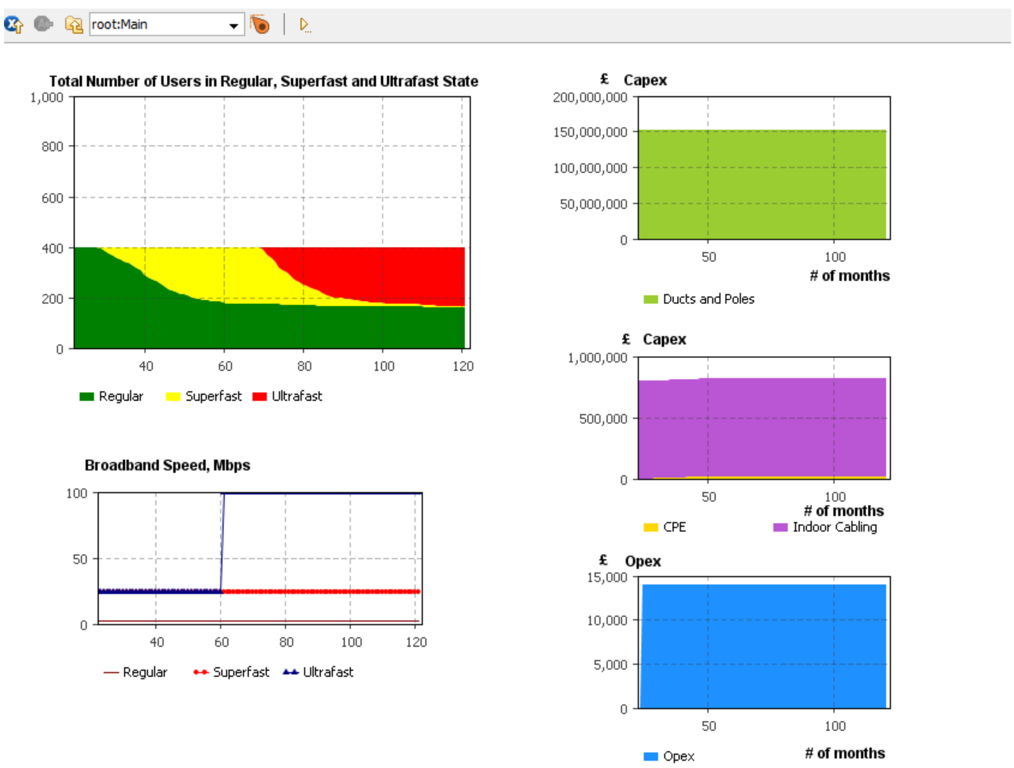

Figure 5-5 Model Representation: user dynamics and costs

5.4 Basis for Establishing Rigour, Reliability and Validity

The overall research process in general and creating the decision support software tool in particular followed a number of standardised frameworks, methodologies and approaches to establish the rigorous, reliable and valid execution of the current research.

The research outcomes are the logical extension of steps defined in the DBA Handbook by Cranfield University School of Management (SOM). The requirements for and methodology of the DBA deliverables stated in the DBA Handbook constitute the main rigour of the overall research path.

The process of creating the decision support software tool followed the Overview, Design concepts and Details (ODD) protocol (Grimm *et al.*, 2010), a specific methodology for creating ABM models. The main purpose of the ODD protocol is to provide the description of an ABM model to ensure rigorous and reproducible results. The ODD methodology was also summarised in a separate external document which was presented to representatives of Ofcom, a stakeholder that formulated the main requirements for the model.

To ensure that the proposed model reflects a real life business problem and to minimise researcher bias and subjectivity, the decision support software tool was discussed with Ofcom on an iterative basis. From the Ofcom side three main individuals formulated specific requirements for the proposed ABM model:

- Principal of Strategy and Policy, Ofcom
- Competition Policy Director, Ofcom
- Principal Economist, Ofcom

Development of the model was undertaken using a commercial software package AnyLogic 7 University edition. The AnyLogic package is a Java programming language-based development software which utilises three main modelling approaches, i.e. ABM, System Dynamics and Discrete Event simulation. The main advantage of the package is the ability to use a multi method approach to modelling and extensive libraries of reusable Java standard methods and procedures. The standardised yet flexible modelling approach in AnyLogic software ensures replicable results of the research.

The process of creating the software tool on a day-to-day basis followed a SCRUM-like Agile methodology. This is an iterative and incremental framework that is used in software development and other areas to ensure a flexible approach to delivering results. The functionality of the model was summarised in a “wish list”. The main principle of the agile approach is to ensure that the model works within the given scope of functionality after implementation of every step from the “wish list”.

A number of data sources were used in the software development. In addition to the literature which was reviewed over the course of the PS and SLR, the following sources provided quantitative data for duct and pole space availability and continuity, cost models and items for building infrastructures for Greenfield and Brownfield scenarios, and prices for infrastructure elements and works.

- Analysys Mason (2008)
- Analysys Mason (2009)
- Analysys Mason (2010)
- British Telecom (2016)
- CSMG (2010)
- Hoernig *et al.* (2010)

These sources are primarily consulting reports prepared for Ofcom and other telecom companies with respect to IS and are available in the public domain. Since the EP focused primarily on the UK market, most of the data from the open sources sufficiently describe the UK infrastructure (BTOR).

6 RESULTS

6.1 Analysis Methods Embedded in the Prototype

The empirical project is a quantitative research study which uses a combination of numerical and visual data analysis. All the numerical data on user demand, types of user subgroups and their take-up of broadband services, Capex and Opex cost characteristics on the infrastructure supply side, are visualised in graphical form for analysis (charts in presentation window). Also, the presentation window provides visualisation of network coverage using tree topology for Greenfield, Brownfield DPA and Bitstream scenarios (Figure 6-1).

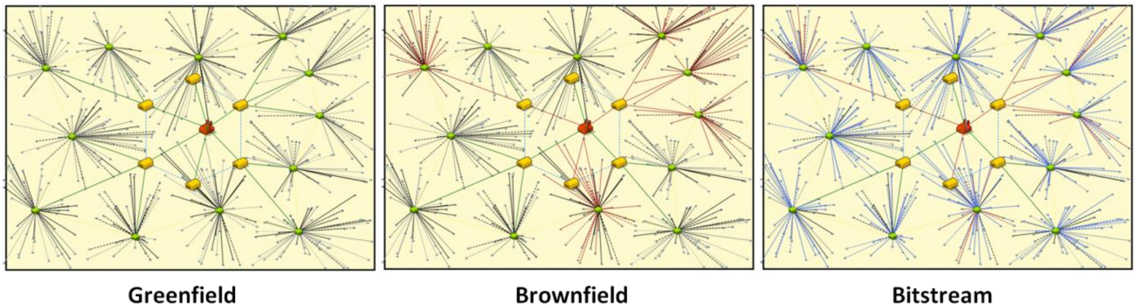

Figure 6-1 Visualisation Analysis for Three Scenarios

Along with visualisation, numerical data analysis is available in the prototype. The numerical data produced by the model are parsed using programming tools into the AnyLogic console environment. The scope and format of output numerical results are customisable to enable aggregated and/or detailed data analysis of infrastructure costs, route availability and continuity, infrastructure elements, user characteristics, etc. Figure 6-2 provides an example of data analysis in the AnyLogic console.

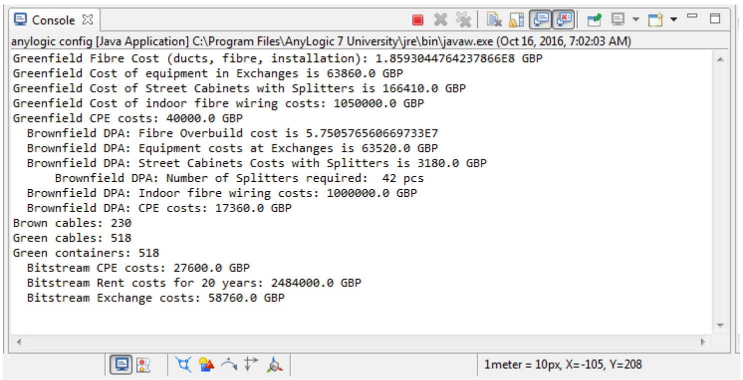

Figure 6-2 Numerical Output Data in the AnyLogic Console

Every model run generates two types of data for analysis: constant and random. The results for costs of equipment in Exchanges, Street Cabinets, Indoor Cabling and CPEs are the same every time the model is run as these calculations use exact number of users and known ratios with predefined constants. The fibre overbuild costs have embedded randomness as every model iteration distributes users randomly leading to different lengths between users and street boxes every time. Moreover, DPA availability and continuity is also randomly defined in the model iteration run, which leads to different outcomes in the Brownfield scenario. Running the model tens of times can generate sets of data on fibre overbuild costs, which can be used further for statistical analysis with a confidence level about the output variables.

At the prototyping phase, comparative analysis of infrastructure scenarios is possible in terms of total costs of building each option (Greenfield, Brownfield, Bitstream). With further development of the demand side at the calibrating phase, e.g. revenue and profits generated by operators in different scenarios, a comparative analysis of relative economic performance of the operators can be conducted.

Randomness is also included in the rates of transitions from Regular to Superfast and Superfast to Ultrafast states for different subgroups of Users which can be used for time analysis. The growth of Superfast and Ultrafast in relation to price changes can be analysed over time using multiple iterations.

6.2 Model Outcomes

This section describes the results which are generated by the decision support software tool developed during the EP.

6.2.1 Initialising Demand

Before the model start-up, the size of the broadband market is set up in variable *userPopulation*. It is done by changing the field ‘Initial value’ in the Properties window of the variable *userPopulation* in the tab ‘Main’. Upon model start-up the market is populated with the users by pressing the check box **1. plant greenfield users**. Iterations were run with different values for user population to evaluate performance of the model. A value of 500 users was selected for reporting as this population provides a good graphical representation of simulation scenarios (Figure 6-3).

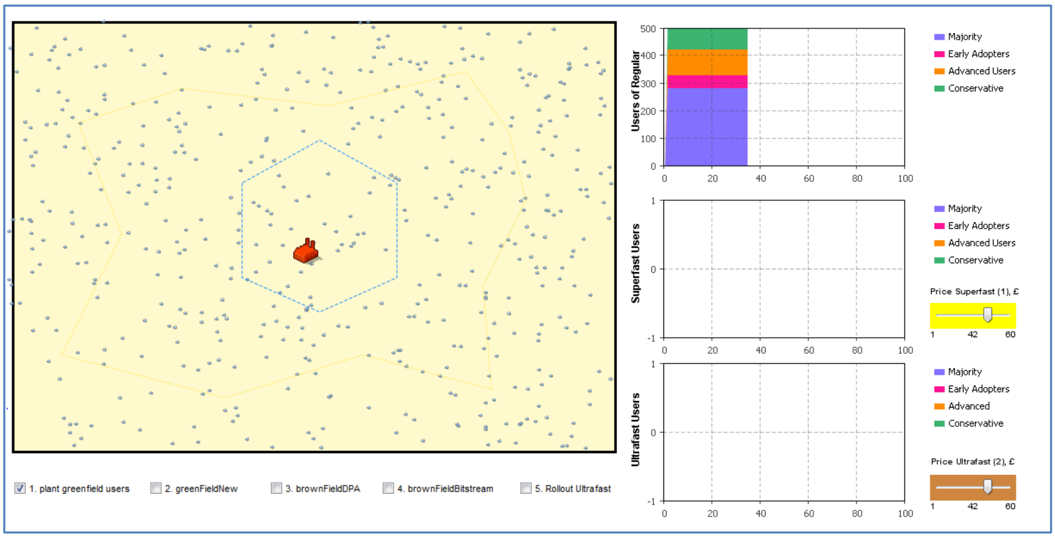

Figure 6-3 Model Results: Simulating Demand

In this simulation, all users are distributed randomly over a rectangular territory and all initially assigned to the state user of ‘Regular’ broadband. Within the main population users are further distinguished by types (Majority, Early Adopters, Advanced and Conservative) in accordance with custom distribution defined in the program settings.

In the prototype, the demand for broadband services specifically means the demand for infrastructure availability. Users are viewed as customer premises where the broadband network terminates. The sum of users represents a fixed demand which is assumed to be static and not changing with the time. The functionality of delivering various bandwidths to users over different infrastructures is not realised in the prototype.

6.2.2 Building Infrastructure: Greenfield

The Greenfield scenario is initiated when the checkbox **2. greenFieldNew** is pressed. Upon this action the following results are obtained:

- Exchanges and Street Boxes are placed in given places (points of polygonal shapes)
- Containers are built to connect Exchanges with the Metro Node
- All Street Boxes check minimal distance to the closest Exchange and connect with a duct container
- All Users check minimal distance to the closest Street Box and connect with a container. The type of a container in the final drop (either duct or pole) is defined by the formulae 7-1. If condition 7-1 is not satisfied then a duct container is built in the final drop.

$$Uniform\ P_{Pole} < 0.2 \qquad \textbf{(6-1)}$$

where

$Uniform\ P_{Pole}$ Probability of a pole container following uniform distribution to represent an assumption that poles are built in 20% of final drops.

- When a container is built it is created with cables inside. The number of cables follows uniform discrete distribution (1, 3) to represent an assumption that it is equally likely to have 1, 2 or 3 cables inside a container (duct or pole)
- Visual representation of the Greenfield infrastructure is created (Figure 6-4). In the final drop between a Street Box and a User duct containers are

represented by solid and pole containers by dotted lines. Different shades of grey represent the number of cables inside, i.e. darker colour corresponds to fewer cables.

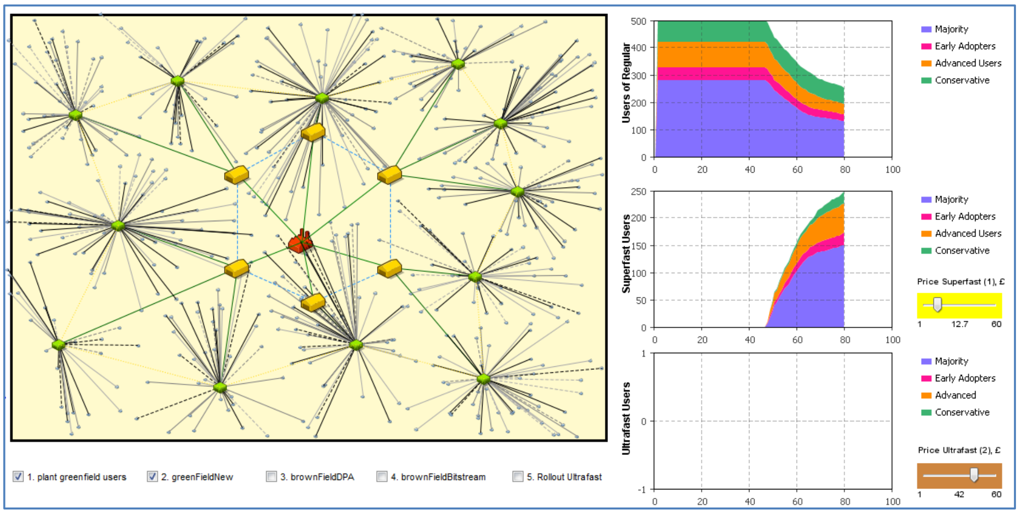

Figure 6-4 Greenfield Infrastructure: Superfast Available

- By changing prices for Superfast broadband using the slider on the model interface, Users move from Regular to Superfast state. Various types of users transit to Superfast with different rates.
- By pressing the checkbox **5. Rollout Ultrafast** and changing prices for Ultrafast broadband using the slider, Users move from Superfast to Ultrafast state. Various users transit to Ultrafast with different rates (Figure 6-5).

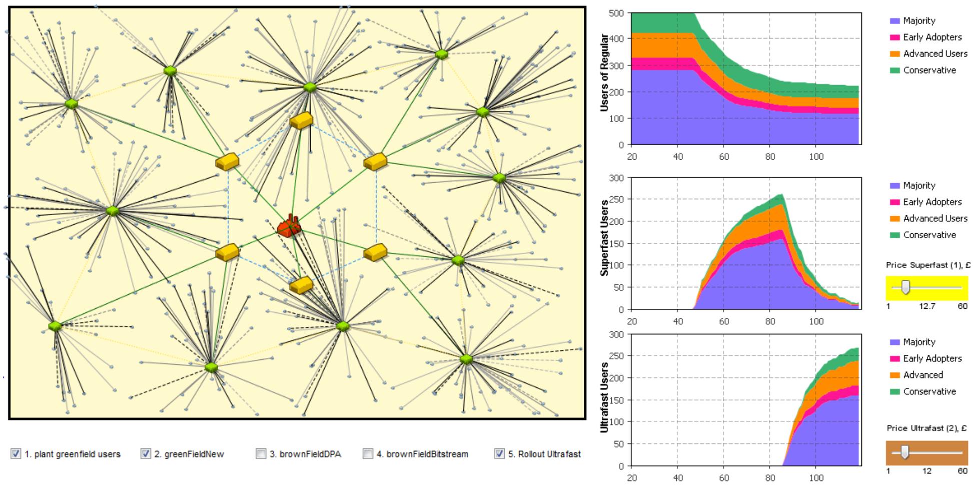

Figure 6-5 Greenfield Infrastructure: Ultrafast Available

1. When the Greenfield scenario is run, the CAPEX and OPEX costs of the Greenfield infrastructure are displayed in the console (Figure 6-6) and graphics (Figure 6-7).

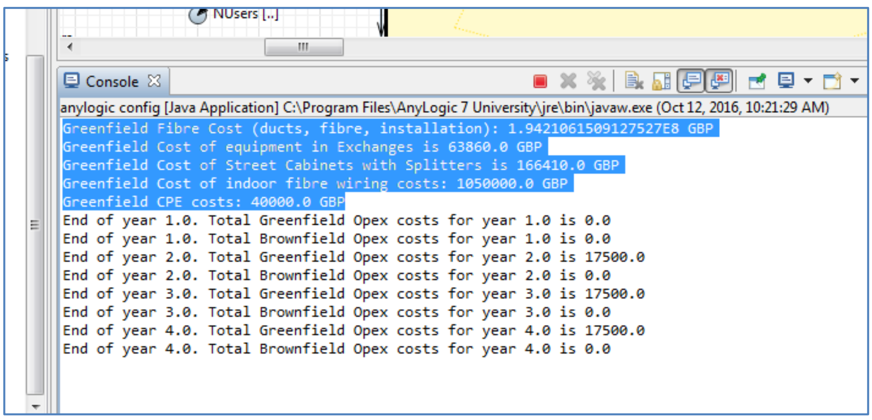

Figure 6-6 Costs of Greenfield: Numeric Representation

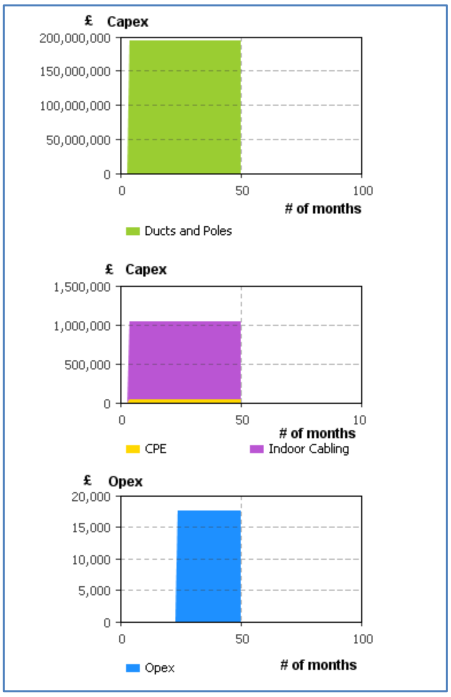

Figure 6-7 Costs of Greenfield: Graphic Representation

The charts in Figure 6-7 visually represent CAPEX and OPEX costs with flat values over time as the costs of building infrastructure are calculated in the model once, upon model start-up. OPEX costs are calculated starting in the following year after the main infrastructure is built. Graphics are interrupted in the 50th month of the simulation as this was the time the screen shot was taken (values remain flat over the length of the simulation).

6.2.3 Building Infrastructure: Brownfield

Building the Brownfield scenario is executed by checking the Checkbox **3.brownFieldDPA** during the model run**.** This action calls for methods which check the availability for additional cables insides containers, define path continuity from a user to Metro Node, install cables in case it is possible, calculate economics of the whole Brownfield infrastructure and visually represent the Brownfield infrastructure in brown colour (Figure 6-8).

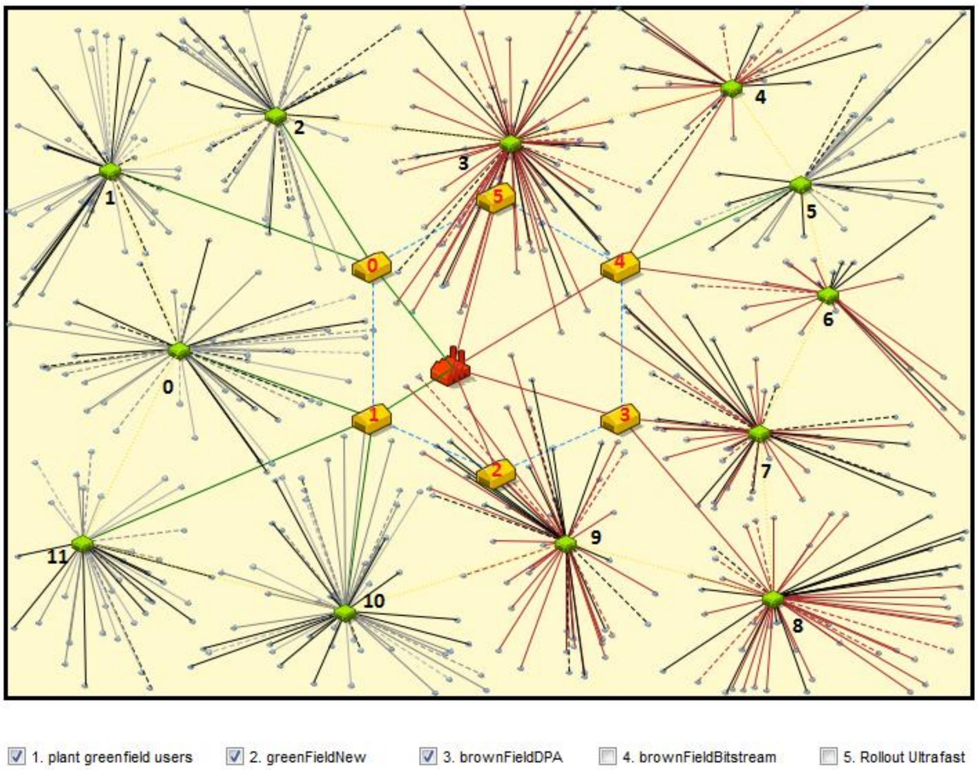

Figure 6-8 Model Results: Brownfield Infrastructure

6.2.3.1 Checking Availability in Ducts and Poles

Availability in ducts and poles is defined by parameter *max_cables* which is an attribute of a container. In the model, when a container is built in the Greenfield scenario each container is created with cables inside. The number of cables follows uniform discrete distribution (1, 3). In other words, each container includes 1, 2 or 3 fibre cables inside. If the parameter *max_cables = 1* then the appropriate container does not have free space for laying addition cable. In Figure 6-9 each container is shown with its own value of the parameter *max_cables.* The highlighted segment in Figure 6-9 indicates that:

- User 2 is connected to Street Box 10 with Container 20 which has only one fibre cable inside. No more additional cable is possible.
- Street Box 10 is connected to Exchange Node 1 with Container 16 which has two cables inside. Laying additional cable is possible.
- Exchange Node 1 is connected to Metro Node with Container 1 which has three cables inside. Laying additional cable is possible.

- Since Containers 16 and 1 allow laying one more additional cable inside but Container 20 does not, the whole path continuity between User 2 and Metro Node does not exist (indicated with ‘false’).

6.2.3.2 Checking Continuity

During execution of the Brownfield DPA scenario, the model checks path continuity from any user to Metro Node and prints out the results for each user in the AnyLogic console screen. The path continuity is a list of all nodes and all containers between a user and Metro Node. The highlighted rows in Figure 6-9 represent the results of continuity checking for User [2].

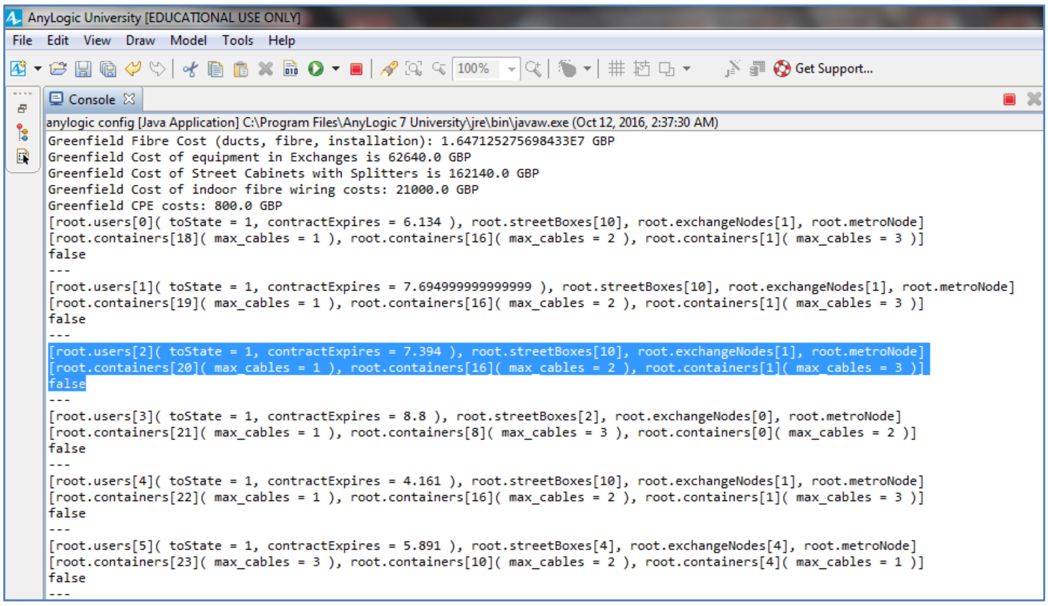

Figure 6-9 Model Results: Checking Path Continuity

Broadband by an incumbent operator is delivered to User [2] from the Metro Node through Exchange [1] and Street Box [10] using Containers [20], [16] and [1]. The results show that in Container [20] the maximum number of fibre cables is one (**max_cables = 1**) which indicates that this cable belongs to the incumbent and additional fibre cable from an alternative operator cannot be installed. This result is shown with the sign ‘false’ and in the graphical representation of Brownfield this path will retain a green colour. Based on these results the alternative operator can make an estimated decision on what clusters of users can be covered if a new Brownfield infrastructure is built.

6.2.3.3 Unsatisfied Demand for Alternative Operators

Checking space availability and path continuity allows estimating clusters of monopolistic coverage within the Greenfield infrastructure by the incumbent operator. Figure 6-8 shows the results of a particular simulation when the Brownfield DPA scenario is imposed on the Greenfield infrastructure.

The results shows that clusters belonging to Street Boxes [3], [4], [6], [8] and [9] can be covered by an alternative operator with the Brownfield infrastructure. However, the remaining clusters of users indicate monopolistic coverage by the incumbent due to space and path unavailability (no DPA possible). This information helps make a decision by an alternative operator on infrastructure development in areas with unsatisfied demand. It also enables the regulator to analyse the market situation in light of stimulating infrastructure-based or service-based competition.

6.2.4 Renting Infrastructure: Bitstream

The Bitstream scenario is imposed on the Greenfield scenario assuming that the incumbent operator built its own infrastructure and lends it to an alternative operator. The alternative operator expects to win a certain market share and digitally connect acquired subscribers under wholesale agreement with the incumbent.

In the model, after populating users (checkbox **'1. plant Greenfield users'***)* and building Greenfield (checkbox **'2. greenFieldNew'***)* the Bitstream is initiated by pressing the checkbox **'4. brownFieldBitstream'**. This runs a function that installs Bitstream CPEs to a given percentage of subscribers. Figure 6-10, Figure 6-11 and Figure 6-12 represent the results of the Bitstream scenario under the assumption that the alternative operator expects to win a 20%, 50% and 70% market share respectively.

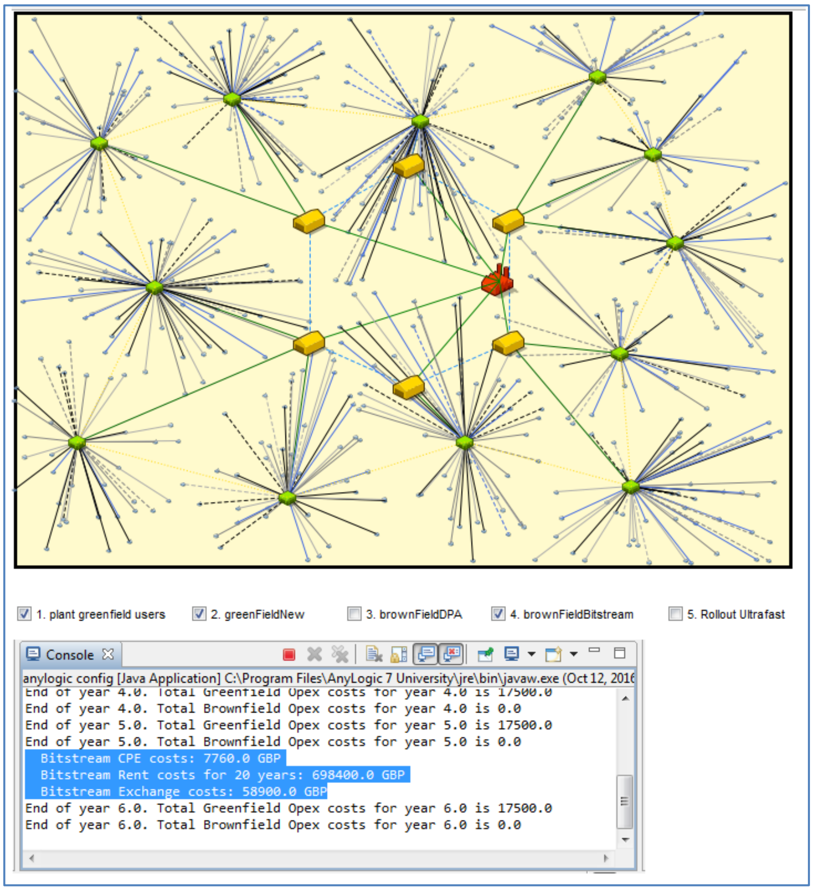

Figure 6-10 Model Results: Bitstream with 20% Market Share

Bitstream users are connected with containers with the blue colour. The economics of Bitstream are displayed in the console. The annual Bitstream rent costs are taken from the BTOR price list and calculated for 20 years to make it comparable with CAPEX from the Greenfield and Brownfield scenarios.

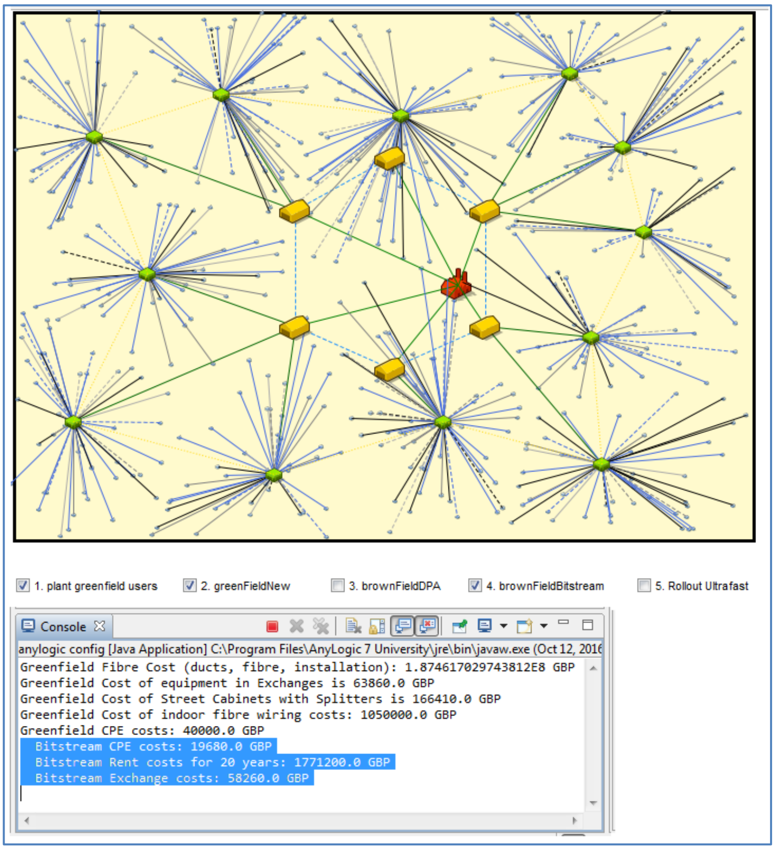

Figure 6-11 Model Results: Bitstream with 50% Market Share

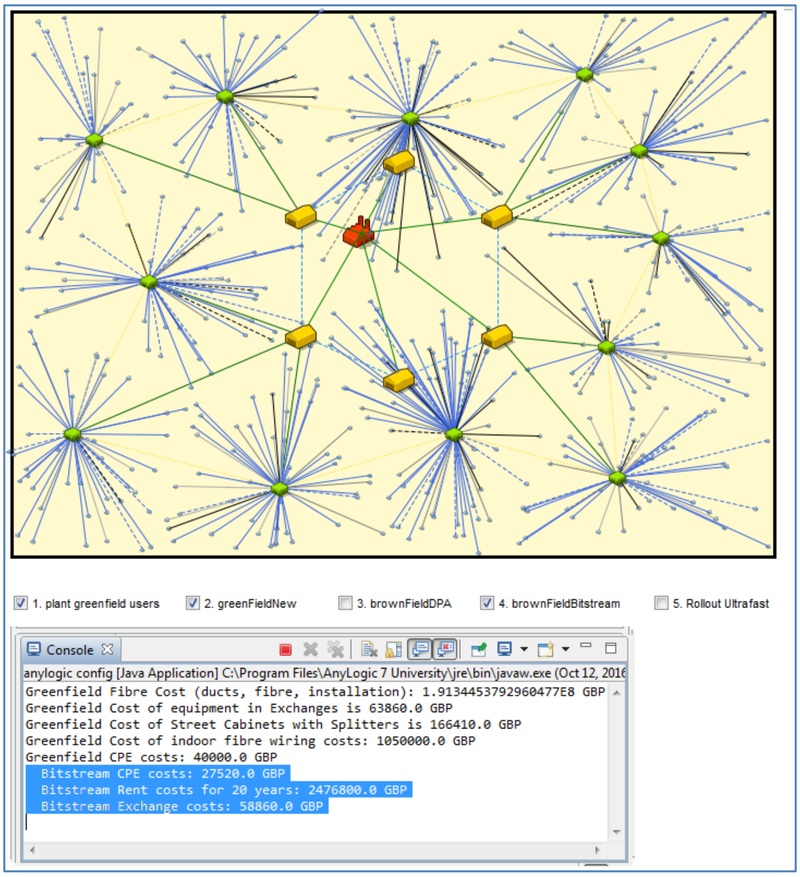

Figure 6-12 Model Results: Bitstream with 70% Market Share

The results of all Bitstream scenarios show the major costs are those for rent of channels from the incumbent operator.

6.2.5 Optional Results

By running selected methods from the Java Class “CostModel”, various optional results can be obtained. For example, by calling a method **numOfSplitters(users)**, the number of splitters to be installed in Street Boxes is calculated (Figure 6-13).

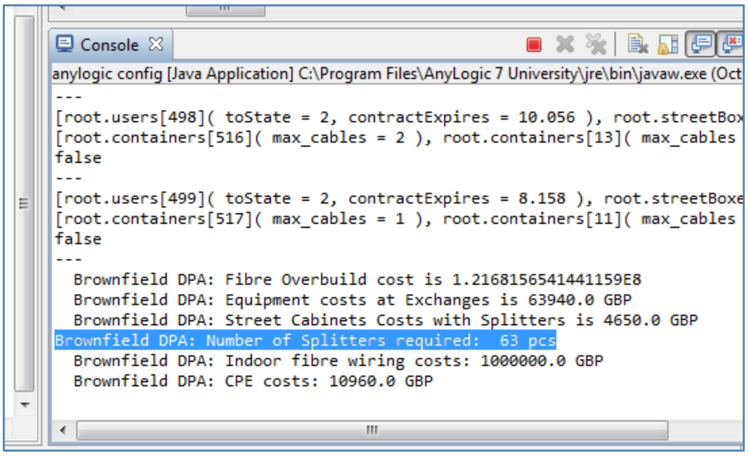

Figure 6-13 Optional Results: Number of Splitters in the Brownfield Scenario

Similarly, results for the quantity of ODFs and OLTs, lengths of ducts and poles with appropriate cost characteristics, number of CPEs connected, etc. can be calculated.

7 DISCUSSION

Formulated from the overarching research question, the aim of the empirical project is to further investigate the topic of IS in telecommunication, particularly duct and pole access (DPA) in wireline networks, and address the following problem:

‘What does it take for a new operator to become competitive in the ultrafast services landscape assuming strategies are limited to building own infrastructure through BTOR duct and pole access or buying a “bitstream access” using existing BTOR networks?’

This study set out to design a decision support software tool on the basis of ABM which would help the UK telecom regulator Ofcom to answer the following model questions:

1. How do Ofcom interventions to regulate BTOR DPA and overall physical availability of ducts and poles influence an operator’s decision to build its own ultrafast network or buy “bitstream access” from BTOR in a particular location in the UK?
2. What is the optimal price range of broadband services delivered through new ultrafast networks which would enable sufficient investments from alternative operators and generate sufficient demand by end-users?

This EP has shown that creating a decision support software tool is feasible and delivered the first design of the software prototype. The developed prototype fully meets the objectives of the research as it is able to recreate a generic telecommunication market with an incumbent and an alternative telecom operator on the supply side, and population of users with different behaviours on the demand side.

The main result of this phase is that it is able to simulate three major infrastructure scenarios, i.e. Greenfield, Brownfield DPA and Bitstream in connection with the market and changes in user behaviour. The current prototype functionality is able to examine various research aspects and provide the following insights.

7.1 Insights from the Model Outcomes

7.1.1 Network Topology is a Key to Precise Results

Network design in the prototype follows a generic star topology, i.e. all exchanges are connected to one Metro Node, Street Boxes are connected to the closest Exchange, a number of Users are connected to one Street Box on a one-to-one basis (Figure 6-5). This topology results in a great number of containers between nodes with relative distances that are comparable with each other. This is not the case in reality. Unexpectedly, these assumptions have resulted in costs of laying fibre through ducts or poles of approximately 190 Million GBP for only 500 User premises (Figure 6-6). In the same model set-up for 500 Users Exchange costs = 63,860 GBP, Street Boxes costs = 166,410 GBP, Indoor wiring costs = 1,050,000 GBP and CPE costs = 40,000 GBP.

The above analysis does not enable the determination of infrastructure costs at the prototyping stage accurately; however, the model outcomes confirm that civil and engineering works are the major cost elements of the building infrastructure, which is consistent with industry benchmarks. In order to obtain more precise results, it is recommended to follow real topology during the calibration phase and use different adjustment coefficients to arrive at more realistic distances and costs. In the real case scenario a set-up with exact locations for network elements can improve the accuracy of calculations.

7.1.2 Civil and Engineering Works are the Major Costs

As pointed out in Section 7.1.1, the major costs of building a physical infrastructure are costs of laying ducts with fibre. In the model set-up, after several iterations of Greenfield scenarios, the costs of containers are around

180-200 Million GBP. The costs of Brownfield DPA containers overbuild in different iterations are in the range of 20-50 Million GBP. The Bitstream scenario under 70% market share (CPEs, Exchange equipment, Rent of channels) for 20 years, results in costs less than 3 Million GBP under the same model set-up. Investments under the Bitstream scenario are significantly less than in the Capex scenarios.

7.1.3 Results Contribute to Debate on "Ladder of Investments"

The cost results under various scenarios are broadly consistent with the real business cases when alternative operators can enter telecommunication markets with fewer investments. This is also consistent with the theory of 'Ladder of Investments' (Cave, 2006) when new entrants step onto the first rung of the LoI with service-based competition and then climb the ladder to move to infrastructure-based competition. This theory was debated by Bourreau *et al.* (2010). The decision support tool can contribute an interesting insight to this debate on the subject of the 'Ladder of Investments' after the calibration phase, once revenue streams from the market are simulated.

7.1.4 Effect on Competition Needs Additional Investigation

The revenue side would allow the projection of income for an alternative operator to simulate and check a potential decision of an alternative operator to move from service-based (Bitstream) to facility-based (Brownfield) competition. The previous analysis of mandatory versus voluntary sharing in the SLR revealed that various studies show controversial results on the effect of mandatory sharing. Various researchers argue that mandatory IS was not welfare enhancing (Crandall, 2005), did not enable broadband penetration (Crandall *et al.*, 2013), and did not lead to an increase in competition (Hazlett, 2006) and infrastructure investment (Cave, 2014). By enhancing functionality on operators' behaviour in the calibrating stage, the model can contribute to the above-mentioned academic debate and investigate the effect of DPA on competition.

7.1.5 Monopoly Creates Uncovered Demand

Figure 7-1 demonstrates the results of several iterations of the Brownfield scenario.

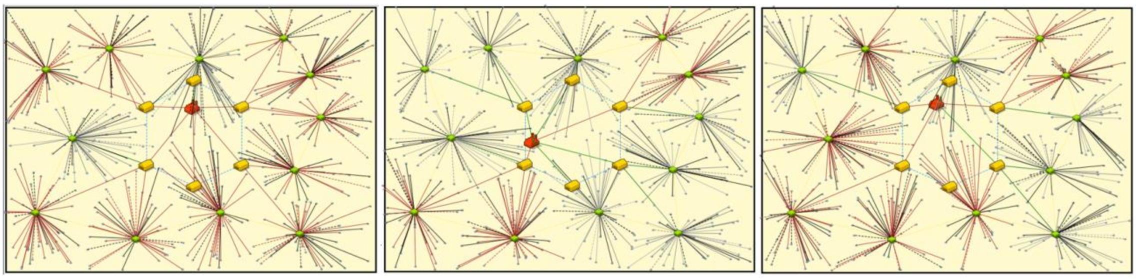

Figure 7-1 Brownfield Scenario: Uncovered Demand in Several Iterations

Depending on the availability of ducts, certain areas can be covered by an alternative operator infrastructure (brown clusters). Other areas remain under monopolistic coverage of the incumbent operator (grey clusters). Even with controlled parameters on duct availability, the results of iterations constantly demonstrate that 100% coverage by the Brownfield infrastructure is not possible using BTOR DPA access.

This indicates to a potential decision maker (e.g. regulator or alternative operator) that decisions other than mandating DPA access can be supplemented; for example, a combination of DPA access with Bitstream, subsidising alternative infrastructure development in monopolistic clusters or creating incentives to share infrastructure elements with other utilities.

7.1.6 DPA Availability is a Substantial Risk Factor

Running several experiments of the Brownfield scenario also leads to a conclusion that DPA availability is hard to predict in areas where BTOR exact data are not available. Even if uncovered demand is estimated for a certain area, the exact investment decisions on covering exact districts or areas can be difficult to estimate. Such uncertainties would prevent investors from building alternative infrastructures as they constitute substantial risk factors. Regulators can develop special programmes to cover the risks to further incentivise alternative operators.

7.1.7 DPA Continuity Further Sharpens Uncertainty

If DPA availability looks at possibility to lay alternative fibre cable in a particular link between nodes, the DPA continuity is checking combined probabilities of space availability in sequential routes from a User premise to the Metro Node. DPA continuity further sharpens uncertainty of successful implementation of alternative infrastructure and potentially increases amount of necessary investments. The significance of this finding is that the model can predict DPA availability for covering smaller areas whereas for larger metro areas the model functionality for checking DPA continuity plays a more important role.

7.1.8 Limited Functionality of Transition to Ultrafast

Current prototype functionality simulates that Users move to Ultrafast broadband under two assumptions: existing Superfast infrastructure allows the delivery of Ultrafast broadband (**'Ultrafast available'**) and the price for Ultrafast for various subgroups satisfies subscribers' needs. In relation to the EP objectives, this is the main limitation of the current model, which needs further development.

7.2 Prototype-Based Answers to Model Questions

On the one hand, the developed prototype functionality provides a limited basis for addressing the whole real life picture of broadband infrastructure development in the UK. On the other hand, the model is able to contribute to model questions raised by Ofcom.

In relation to model question 1 on Ofcom interventions to regulate BTOR DPA, results of prototyping validate that DPA availability and continuity are the major determinants of successful investments decisions by alternative operators. Even with controlled parameters of DPA, availability and continuity simulations provided results that are too general to make a justified investments decision. Simulations confirm that potential cluster demand for alternative infrastructures exist, which is currently covered by monopolistic BTOR. Simulations also confirm that Bitstream remains a relatively low risk scenario for entering the market. This confirms the views of Maxwell *et al.* (2007) who state duct access is not a regulatory 'silver bullet' but a regulatory remedy that must be used with other wholesale remedies.

In relation to model question 2 on the optimal price of a broadband service to generate sufficient demand by subscribers and enable sufficient infrastructure investments, the software prototype is able to simulate basic demand for Ultrafast services but fully addressing model question 2 needs further development under a real case construct.

8 CONTRIBUTIONS

The research described in this thesis has theoretical, methodological and empirical contributions.

8.1 Theoretical Contributions

The theory of the ladder of investments (LoI) (Cave and Vogelsang, 2003; Cave, 2004, 2006) is extended to include hybrid network and platform-based competition and investment, i.e. between the service economy and the facility economy. The first contribution described is about hybrid network competition, which is represented in the model by the Brownfield scenario. It is a step on the LoI with the ability to add new wires and cables by sharing space within incumbents' ducts and poles. The new operator is constrained by the location of the incumbents' assets and so can serve only existing customers. This requires some investment in physical network assets and is a *new* level of competition and innovation.

The next contribution is about a telecoms duct and pole case study and model. The majority of the literature and academic debate on the theory of LoI (Jorde, Sidak and Teece, 2000; Cambini and Jiang, 2009; Bourreau *et al.*, 2010) focuses on LLU. The current study enriches the body of knowledge by focusing on another form of IS, i.e. ducts and pole access.

The top most level of investment is required to build a new network (or facility) infrastructure. Typically this would arise in the event of a new housing estate. This is represented as the Greenfield Scenario in the model. There is IS but it is from the telecommunications exchange upward, i.e. new infrastructure is required to the exchange or at least to street cabinets.

At the lowest step on the ladder of investments, the regulator might incentivise service-based competition, in which new operators are able to lease incumbent operators' network assets. This is service economy competition. It requires the least level of investment for a new operator and allows the new operator to develop a customer base from which it might invest in higher steps on the ladder of investment. This is represented in the model by the Bitstream scenario.

The outcomes of the research consider the issue of interdependencies among incumbent and alternative operators in a telecommunication market. Brownfield and Bitstream scenarios specifically represent two-sided relationships where alternative operators act as input providers to broadband users and at the same time purchase infrastructure capacity from the incumbent. This provides a supportive contribution to the discussion on the theory of platform markets (Bauer, 2010) and its importance for modern regulatory practice. In comparison to traditional regulatory frameworks, e.g. theory of monopoly regulation (Kahn, 1971), and essential facility doctrine (Pitofsky, Patterson and Hooks, 2002), the platform markets perspective provides benefits in recognising the hybrid nature of intermediary organisations in network industries (Bauer, 2014). The contribution extends platform markets to include not just facility and service economics but also hybrid economics via the Brownfield scenario.

The study also demonstrates that the focal point for innovation and investment into IS, and therefore into telecommunications competition, is not in the telecommunications exchange network but in the customer access network. These are many in number, and are heterogeneous in spatial characteristics as well as population demand characteristics.

The study considers investment over all time periods and relates these to the ability of consumers to access networks of increasingly fast speeds. There is a non-linear relationship between investment and access to superfast and ultrafast networks. The simulations run with the help of a software model found that mandatory sharing imposed on an incumbent’s infrastructure does not necessarily lead to the development of alternative infrastructures and investments from new competitors. The volume and speed of new revenue streams generated by switched users towards an alternative operator does not guarantee significant return on investments. This contribution is consistent with the results from SLR and supports the academic critique of LoI theory.

The study uses the ABM approach to simulate complex relationships between users, operators and infrastructures. This approach supports the notion of telecommunication viewed as an ecosystem (Fransman, 2010). Fransman suggests that in a socio-economic ecosystem ongoing 'symbiotic' interactions between firms, suppliers, competitors and users can generate 'new knowledge'. The software prototype analyses how ducts and poles availability on the supply side and various types of broadband users on the demand side affect innovation, investment and take-up of the broadband network. The study contributes to the theory that telecommunications provision is an ecosystem and a complex system that is continuously evolving and adapting.

Bauer (2014) further develops the concept of ecosystems and applies a system-theoretic approach to ICT regulation. He claims that the four aspects of dynamic systems are incompletely described in academic literature: (i) system interrelatedness, (ii) complex patterns of feedback and non-linearity, (iii) emergent properties of ICT systems, and (iv) existence of multiple dynamic equilibria in systems. The complex system perspective of current research and ABM in the software prototype takes the systemic perspective and contributes to the first three of these gaps. The study focuses on interrelatedness between and among agents, and addresses the issue of feedback on broadband subscription and non-linearity of broadband take-up by different groups. The model exposes the learning of users and emergent patterns of their behaviour rules. Further enhancement of the model post-viva will also address the different infrastructure decisions of operators, which can represent multiple equilibria points in the whole ecosystem. The contribution to theory will be the rules which generate multi-equilibria.

8.2 Methodological Contributions

The study is unique in utilising a Systematic Literature Review approach for investigating various concepts of IS in core network industries, i.e. water, energy, telecommunication and transportation.

There is also novelty of the research by adopting a SCRUM-like agile methodology for model development (Ard, Davidsen and Hurst, 2014). An informal "wish list" with the set of desired model functionalities was summarised and used for scoping the model. This approach contributes to the body of knowledge as it applies modern software development standards in the field of academic research and scientific simulation development. The study also contributes to a particular field of programming languages and methods of modelling as it uses simulation software AnyLogic with built-in Java programming functionality.

This study uses as a basis the ABM framework for energy infrastructures by Chappin and Dijkema (2010) and Varga *et al.* (2014) for any infrastructures. Chappin and Dijkema (2010) suggested the five main components for building ABMs in energy infrastructure systems, i.e. (i) system representation, (ii) exogenous scenarios, (iii) design of transition assemblage, (iv) system evolution and (v) impact assessment. By simulating IS in telecommunication networks this research contributes to the field of complex systems applied to the regulation of infrastructure systems. However, the research also shares the limitations of this framework, as representation of the system largely depends on the individualistic focus of a researcher, and outcomes of the model do not necessarily show "what will happen but what may happen" (Chappin and Dijkema, 2010).

Certain authors use complex systems research approaches aligned with the study (Brown *et al.*, 2004; Dobson *et al.*, 2007; Herder *et al.*, 2008; Grove and Baumann, 2012). Bauer (2010) states that in the area of regulation and investments in telecommunication networks, simulation models and experimental approaches have become a 'promising avenue' as they go further in investigating interdependencies, multi-equilibria systems, joint outcomes of supply and demand sides (de Bijl and Peitz, 2004; Beltrán and Sharkey, 2009; Demaagd and Bauer, 2011; Mirza and Beltrán, 2014). Methodologically, the agent-based model approach represented a system with interdependencies between buying preferences of users, infrastructure scenarios by operators and regulatory actions for stimulating DPA.

With its complex system perspective, the current study provides a methodological contribution to the existing body of knowledge as it enriches the research arsenal of applied simulation and modelling techniques, such as queuing theory (Choi and Kim, 2010), genetic programming method (Demaagd and Bauer, 2011), and ABM (Mirza and Beltrán, 2014). The model uses the ABM approach for the simulation of joint outcomes of supply and demand side and also utilises Brownfield and Bitstream scenarios as examples of the two-sided economic framework (Beltrán, 2012; Economides and Tåg, 2012).

The integration of demand and supply side in one ABM simulation constitutes the major methodological novelty of the study. This contribution is further strengthened as the supply and demand sides are also hybrid but integrated approaches. The demand side is represented by state charts for user behaviour whereas the supply side is modelled with network nodes connected by duct and pole routes. The supply is represented by access network modelling routes from a metro node over exchanges via street boxes to customer premises. Modelling network topology with separate nodes, simulating routes between nodes with real data describing continuity inside ducts, and factoring lengths of routes for calculation of civil and engineering costs, all constitute significant methodological contributions.

The model uses a distinct approach of modelling changes in user behaviour as transitions between behavioural states, which are performed based on various factors, e.g. external messages from other agents, market price changes, contract expiry dates, and probabilities of user transitions. The model also differentiates among different users in terms of their adoption preferences. This is critical to why the ABM approach was adopted, i.e. to represent heterogeneity of consumers and their characteristics of behaviours. The supply side uses real data of a sample of the whole telecoms network on route continuity and availability of free space inside ducts to create a virtual probabilistic network. These data are taken from a real sample size of ducts representing less than

1% of Openreach infrastructure, which underlines the advantage of ABM over statistical methods for simulating nationwide infrastructure development.

The software model is a hybrid method, which also uses visualisation techniques (Basole, Park and Barnett, 2015), statistical distributions for sub-user groups and probability of outcomes, and an economic framework for cost analysis (Hoernig *et al.*, 2012). In terms of visualisation, the model creates abstract spatial representations based on secondary data of telecommunications installations. This random but representative spatial display is an essential communication tool for regulators and decision makers. Visualisation is used both for representing the changes on the demand side when users transit from different states and on the supply side when different infrastructure scenarios are modelled. A particular advantage of the model is that visualisation is dynamic and reflects changes when certain controlled parameters are changes (e.g. price of broadband).

A particular methodological contribution of the study is that it simulates infrastructure scenarios based on node topology and route continuity within ABM and at the same time applies a basic economic framework for each scenario using real life industry data. The study uses two distinct methods of building an alternative infrastructure on the basis of an existing one and also a scenario of renting an infrastructure. For both scenarios the model provides calculations of capital and operational expenditures.

8.3 Empirical Contributions

The general topic of the research is IS in telecommunications. The empirical work is related to the particular subject of Duct and Pole Access to British Telecom infrastructure regulated by Ofcom. The DPA example is vital as it is viewed by Ofcom as one of the key factors to stimulating competition in telecoms and developing alternative infrastructures (Ofcom, 2016).

The DPA initiative represented in the decision support simulation model contributes to the discussion of successful implementation of the BDUK programme. This study (the model and its implementation to demonstrate the DPA initiative) also contributes to the professional body of knowledge as it uses real data from various sources for academic purposes. The data on availability and continuity of DPA were taken from Analysys Mason (2009, 2010) performed for Ofcom. The economic framework was performed using Analysys Mason (2008) and CSMG (2010). The exact data on renting telecommunication equipment are taken from BTOR price lists (British Telecom, 2016).

The conducted SLR analyses IS in the water, energy, telecommunication and transportation network industries, and specifically contributes to the topic of convergence and superimposing with other utilities.

9 IMPACT ASSESSMENT

The Impact Assessment (IA) section provides evidence of the engagement with practitioners and policy makers in Kazakhstan and the UK and how this engagement has contributed to the evolution of research focus and design. The IA reports results of engagement with the UK regulator Ofcom and the Kazakhstani regulator to describe the potential and actual research impact on wider policy and practices.

9.1 Evidence of Engagement

According to the original impact plan, four major groups of beneficiaries of the research are Regulators, Businesses, Users and the Professional Community (Figure 9-1)

Figure 9-1 Beneficiaries of the Research

The following sections provide descriptions of the evidence of engagement with each group of beneficiaries.

9.1.1 Engagement with Regulators

The engagement strategy with regulators was planned on three levels: (i) focused national, (ii) regional and (iii) global. The focused national engagement path considered interaction with NRAs from Kazakhstan and the UK. The regional engagement direction targeted regulators from the former Soviet Union countries through the Board of Operators (BO) of the Regional Commonwealth in the field of Communications (RCC) and Council of Regulating Authorities (CRA). The global engagement thread viewed the annual Global Symposium for Regulators (GSR) organised by the International Telecommunication Union (ITU) as a main channel for communicating research outcomes to regulators worldwide.

9.1.1.1 Communicating with NRA in Kazakhstan

During the Empirical Project (EP) stage in 2016, a formal presentation of the research and software simulation model was given to the Deputy Chairman of the State Control Committee (SCC) in the Sphere of Communication, Informatization and Media under the Ministry of Information and Communication, which is responsible for regulation and policy making in Kazakhstan. During a second presentation the elaborated decision software tool was presented to Chairman of the SCC on April 17th, 2017 in Astana. The Chairman underlined the point that the SCC is consistently moving towards increasing IS practices in Kazakhstan and that this research can contribute to this process by providing external competence and expertise. The feedback after the presentation is presented in the official letter from the Kazakhstani regulator (see Appendix E ‘Testimony from Kazakhstani Regulator’).

9.1.1.2 Communicating with Ofcom in the UK

Engagement with the UK regulator Office of Communications (Ofcom) has significantly defined the scope of the EP and functionality of the simulation model. It started with the publication of the Digital Communications Review (DCR) (Ofcom, 2016). According to Section 4 of the DCR, Ofcom is to promote competition and network investments based on improving access to Openreach's underground ducts and telegraph poles (Duct and Pole Access or DPA) for alternative operators. Since DPA is a typical example of passive IS, a proposal from Cranfield research team to Ofcom was formulated to simulate infrastructure development scenarios in the EP. Ofcom became interested in Cranfield research and invited relevant staff to contribute to meetings and provide feedback.

During the EP phase in the period May – December 2016, there were four communication events between Cranfield research team and Ofcom officials. The first version of the software model was presented to Ofcom on 10th November, 2016 at Ofcom's offices in London. A full demonstration of the simulation model with infrastructure scenarios, economic framework and subscriber state charts was delivered. The prototype was presented to Ofcom in May 2017.

The process of engagement with Ofcom and its DPA initiative for broadband infrastructure development has shaped the research process significantly. The scope of the software model, the type of IS (DPA), agents' behaviour and infrastructure scenarios are defined by Ofcom requirements. Even though Ofcom was specifically interested in the effect of DPA on alternative infrastructure development and investments, the resulting model was set up with generic parameters (number of users, number of operators, generic incumbent and alternative infrastructure, etc.) and can be easily applied to the context of a different geographical area (e.g. town, county, region, country). With the current set-up, the model provides the capability to assess the effect of DPA introduction and is location-specific.

Ofcom presented a letter of testimony which is not attached to this thesis due to confidentiality requirements from the UK regulator.

9.1.1.3 Engagement with NRAs on Regional Level

On the regional level of Commonwealth of Independent States (CIS) (former Soviet Union countries) the research was presented to the Chairman of the Executive Committee of the BO in March 2016. The software model was presented to the Chairman on April 17th 2017 in Minsk, Belarus where the next BO meeting took place. The feedback on the computation model is presented in Appendix F 'Testimony from the BO of the RCC'.

9.1.1.4 Communicating with Regulators on a Global Level

Approaching the ITU and participation at the GSR is still on the agenda for creating the research impact, as engagement with the practice on such a level requires a thorough step-by-step approach.

9.1.2 Engagement with Businesses

Within the engagement strategy, two operators in Kazakhstan were approached. These are a joint stock company Kazakhtelecom and a telecom company Beeline. Kazakhtelecom is an incumbent operator in Kazakhstan that historically runs the national telecom grid and also has a mobile division providing Long-Term Evolution (LTE) services. Beeline is a Russian mobile company which has also established its fixed telecommunication division in Kazakhstan providing fibre optic digital services.

Within Kazakhtelecom, the research and simulation model were introduced to a technical director responsible for planning and erecting mobile infrastructures. The technical director confirmed that the regulators' perspective of the model is of significant interest for Kazakhtelecom as certain IS policies are unclear in

Kazakhstan, e.g. licensing of Mobile Virtual Network Operators (MVNOs) for spectrum sharing. The model can help Kazakhtelecom Government Relations (GR) to lobby its IS activities.

The model was also presented to a GR representative of Beeline. She confirmed that the particular issue of spectrum sharing is essential for Beeline and other mobile operators in Kazakhstan, as existing licensed frequency bands were not enough for organising LTE for any of the present players. She found the presentation on the model informative but could not come up with a practical application for Beeline operations. The issue of spectrum sharing was straightforward and did not require any additional 'what if' analysis. Local mobile operators bid for frequency bandwidths, pay additional licence fees to government and share resulting bands with others to organise LTE. However, this particular case with spectrum sharing provided significant evidence that various forms of IS are emerging.

9.1.3 Communicating with Professional Community

From the professional community, the current research was introduced to consulting companies McKinsey and Gartner in Astana. The objective of the presentations was to evaluate professional and commercial interest in IS consultancy projects. Consultants confirmed that the topic of IS is on the agenda of their clientele, i.e. regulators and telecom operators, and saw potential for future research in this area.

9.1.4 Engagement with Users

Over the course of the Empirical Project (EP) the Multi-Criteria Decision Making (MCDM) research framework was excluded from the model scope due to Ofcom's interest in the three infrastructure scenarios with a limited number of operators. Therefore, direct engagement with the users did not take place at the stage of the EP. Nevertheless, the current research affects users and brings positive effects for society and welfare by helping to eliminate the digital divide and transform to a networked society.

9.2 Dissemination

As part of the dissemination plan (see Section 4.3.2) an extended abstract on the current research has been submitted to IEEE Communications. The content of the publication will contain results of the conducted SLR and outcomes of the research. The proposed citation for the publication is

Durmagambetov, Y., Varga, L. (2017) ‘Infrastructure sharing: business models, regulation and user needs in network industries’, *IEEE Communications Magazine*, submitted 2017.

Current research was also presented at a UK – Kazakhstan joint “Resilient Structures and Infrastructure” workshop from March 14-17, 2016 in Astana, Kazakhstan. The workshop was sponsored by the British Council Newton – Al-Farabi Partnership Programme and organised by Brunel University London and Nazarbayev University Astana. Thirty seven leading, established and early-stage researchers from the UK and Kazakhstan delivered presentations on their research, discussed the emergent issues facing structures under extreme hazards and identified areas for future research. The IS research was placed in a workshop section dedicated to the mathematical modelling of infrastructure scenarios.

Participating at a Symposium on Executive Doctoral Programmes organised in November 2015 by the British Academy of Management and Cranfield School of Management was part of the dissemination plan. The research was presented to representatives from various academic schools, e.g. Leeds University, Grenoble University, Aston University, Manchester Business School, Nottingham Business School, Henley Business School, and Huddersfield University.

9.3 Impact Evaluation

9.3.1 Impact on Organisations

The research was introduced in four countries (UK, Kazakhstan, Russia, Nigeria), to three NRAs (Ofcom, SCC, Nigerian Regulator), about 20 operators (Kazakhtelecom, Beeline, members of the BO of RCC), two professional events with three universities (Cranfield, Brunel, Nazarbayev University), and two consulting companies (McKinsey, Gartner). Ofcom and the SCC provided iterative feedback on the model. Kazakhtelecom endorsed the creation of one IS working group. A verbal agreement was reached with the BO of RCC to form one working group on a former Soviet Union level.

The initial engagement promotes further impact, which is evaluated using mid- and long-term metrics. In Kazakhtelecom at least one internal project on modern forms of IS is expected in 2018-2019. The software model and the implementation results can motivate the Kazakhstani regulator to incentivise IS policies. The impact will be measured against concrete IS regulatory initiatives undertaken as a result of Kazakhtelecom involvement.

Communication with Ofcom has similar potential to create an impact on regulatory practices in the UK. It also creates an opportunity for Cranfield University to be involved in consultancy projects with Ofcom. The potential impact can be measured by the number and value of consultancy projects.

The research will also produce indirect impacts on other organisations, e.g. suppliers of telecom equipment with IS functionality, service providers and consultancy companies. These stakeholders will benefit from overall increased demand for IS. Other infrastructure providers and utilities will also be impacted on, as IS is affecting other network industries. The overall quantitative impact from these activities will be measured as the monetary value of all signed contracts related to IS.

9.3.2 Impact on Economy

In the IP, four major determinants of IS from the perspective of NRAs were determined, i.e. (i) developing competition, (ii) facilitating innovation, (iii) attracting investments and (iv) increasing welfare. This research contributes to all factors in any potential country where the current research is applied. The direct effect of the research on the Kazakhstani economy is the overall number and value of those IS projects that will be initiated by the SCC in telecommunications and with other network industries. The potential project of Kazakhtelecom for network virtualisation and crowdsourced infrastructure will lead to an increase in the number of new operators. These operators will differentiate themselves based on services. Certain operators will innovate on digital content; other operators will focus towards infrastructure development. Thus, the research will cause a measurable effect on competition, innovation and the level of investments attracted. It also impacts on overall efficiency (savings on duplicated investments and CAPEX, optimised consumer tariffs, preserved scarce national resources) and effectiveness (improved quality of services, additional taxes collected, positive environmental effects).

9.3.3 Impact on Society

The research impact on society is viewed through the lenses of the overall competitiveness of a nation. It is a much broader concept than the economic effect of an initiative. If the impact on the economy focuses more on quantitative metrics, the impact on society is also taking into consideration the qualitative effects. The paradigm of IS is addressing the health, environmental and aesthetic concerns of modern society. IS leads to less usage of common resources, e.g. less public space occupied, fewer natural resources consumed, less disruption from civil works. IS is playing a key role in bridging the digital divide, i.e. bringing digital communication to places where it is not economically viable. It contributes to the digital transformation of a society which in turn affects the whole life of individuals. The exact contribution of this research for society can be assessed in the mid- and long-term (3-7 years). The impact will be assessed by applying a methodology of comparing results with and without IS in a selected country.

9.3.4 Impact on Individuals

With the development of personal gadgets, social networks and electronic services, individuals are moving toward creating and maintaining their digital identity. Individuals are members of various groups in social networks, consumers of digital media, and participants in commercial and government transactions over the Internet. They expect a continuous online experience from telecom companies. The topic of IS, and this research in particular, serves the needs of individuals for infrastructure availability virtually everywhere. It affects individuals as IS increases their ability to work from home. The impact can be measured by the amount of avoided physical mobility costs and wasted time. It creates new career opportunities both in terms of people connected and new types of professions. The research contributes to increased use of infotainment and growth of knowledge. In this case the impact can be measured by the increased amount of Internet traffic type of digital media per individual.

This study creates opportunities for scholars for further research on IS (impact is measured in number of additional research studies). Potential users of the software model will acquire and apply new skills in ABM, Java programming and model simulation; this also creates new career opportunities for those users.

9.4 Summary

The ESRC determines that the impact of a research can include (i) instrumental, (ii) conceptual, and (iii) capacity building[2]. The instrumental impact is measured by how much current policies, business or organisational practices,

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[2] http://www.esrc.ac.uk/research/impact-toolkit/what-is-impact/

strategies or behaviour of stakeholders have changed as a result of a research. The conceptual impact is dealing with understanding of policy issues, supporting a position in a professional discussion, or formulating new approaches to solving a phenomenon. Capacity building views research impact through the acquisition of new applied and personal skills. This report provided evidence of engagement with various research beneficiaries, summarised lessons learned during four years of academic studies, outlined plans for further dissemination and exploitation, and explained the evaluation of actual and potential impact. Table 9-1 summarises impact variety in accordance with the ESRC classification.

Table 9-1 Summary of Research Impact in accordance with ESRC

Instrumental Impact	Conceptual Impact	Capacity Building Impact
- IS projects at Kazakhtelecom scientifically articulated	- Debate on IS between Kazakhtelecom and regulator justified better	- Incorporating philosophical position into problem solving
- Internal competence on network development raised at Kazakhtelecom	- Ofcom DPA initiative attracted attention by Kazakhstani regulator	- Learning Java programming language
- Cranfield founded basis for future potential cooperation with Ofcom	- BO of RCC uses research for understanding new roles of operators. Raised awareness on modern forms of IS.	- Research opens doors to a new career
- Internal project on new forms of IS will be launched at Kazakhtelecom	- Global IS policies may be affected as a result of research presentation at GSR by ITU	- Research expands personal networking
- Research contributes to better efficiency at Kazakhtelecom by optimising its CAPEX and OPEX	- Dissemination via academic journals and practitioners' events contributes to debate on IS practices	- Discipline strengthened to deliver academic results
- A pilot project for IS and outsourcing is considered by BO of RCC	- Impact is generated when best IS practices are summarised and brought from regulatory leaders to followers	- Research inspires colleagues to undertake doctoral studies
- Potential to influence IS practices in Nigeria	- IS research initiatives lead to consolidation and increased cooperation between operators in Kazakhstan and FSU	- New skill acquired to prepare papers for publishing
- Dissemination over social networks, in the form of online courses and professional channels, contributes to practice	- Research showed potential of complex systems to understanding regulatory issues	- Teaching will be launched at internal Academy of Kazakhtelecom and Nazarbayev University
- Use of computational modelling enriches regulatory and business practices	- Research supports IS regulatory initiatives in Kazakhstan and affects industry efficiency and welfare	- Online courses will be prepared on the basis of the research
- Current study creates opportunity for further research on IS in other network industries	- Research contributes to BDUK national initiative by analysing potential DPA scenarios	- Users of software model will develop new skills in ABM and simulation

Instrumental Impact	Conceptual Impact	Capacity Building Impact
- Research affects suppliers of telecom equipment and service providers by enforcing IS initiatives	- Research will cause effect on competition, innovation and investments from piloting modern forms of IS	- Ad hoc research team will be formed to utilise opportunities for further research
- Research contributes to development of policies aimed at less usage of scarce resources	- Research addresses health, environmental and aesthetic societal concerns of infrastructure development	- The model will be enhanced into a product for consultancy or other researchers
- The research topic of IS serves the needs of individuals for infrastructure availability and ability	- Research contributes to bridging digital divide by addressing infrastructure development in remote areas	- Individuals receive more opportunities to work from home from better infrastructure and software availability

As Table 9-1 shows, this research generates actual and potential types of impact which are in line with requirements of the RCUK. The research addresses the topic of IS and contributes to global economic performance, effectiveness of public services and policies, and quality of life, health and work of individuals. The most important multi dimensional impact of the research is that it transforms a nation into a digital society affecting legislation, regulatory policies, business practices, organisational methods, efficiency and effectiveness of economies, and the working and life habits of individuals. It also creates opportunities for scholars for further multi discipline research from a perspective of complex systems, infrastructure development, network industries, and regulation.

10 LIMITATIONS

The final deliverable of the research is a software tool which has been created using certain methodological frameworks, design concepts and approaches, selected data sources, and focused attention on a particular topic of IS in telecommunication, one of many existing software development tools. All elements used in the research have their embedded limitations which contribute to overall quality and rigour of the final deliverable. The following limitations and boundaries of the research must be taken into account.

The study focused on a particular IS method, i.e. duct and pole access, of the telecommunication infrastructure. In a real business construct, underground conduits are often shared with other utilities, e.g. water and electricity. The decision software tool can further take into account the availability of IS with other network industries.

In the software prototype, on the supply side one incumbent and one alternative operator with two potential business scenarios are configured. This construct also assumes that both operators use the same infrastructure technology which imposes a scenario limitation as in telecommunication broadband can be delivered with different technologies (fibre, cable, mobile). The decision support model can be enhanced by including different technologies in simulation.

Operators' strategies in the model are only represented by selecting between three infrastructure development options without taking into consideration market strategies of acquiring market share, generating profit, and competing with other operators. The presence of other players in a real market significantly corrects the outcomes of economic frameworks as competition affects consumer prices and subsequently corporate profits.

Users' behaviour is represented by only three states, i.e. users of Regular, Superfast and Ultrafast broadband. The model can further consider other potential states of subscribers, such as users without Internet access, users of Mobile only. Another limitation of the simulation is that the model does not differentiate between residential and business users. This option can be further developed during the calibration stage.

Decisions of users in the prototype are simple, i.e. they upgrade to better broadband based on infrastructure availability and depending on the price of broadband. The model does not consider for users the differentiation in broadband speed, quality, bundled packages, bandwagon effect and word-of-mouth effect of broadband penetration.

The simulation at the prototyping stage does not consider geographic types and population characteristics. The model construct is generic with the possibility to include more data on size and density of population, age groups, composition of business and residential users, territories to cover, etc. The model can be applied to a real region with actual demographic, geographic and economic data.

Methodologically, the model was created using a wish list approach to software development based on limited requirements from Ofcom. Further requirements from Ofcom can be clarified during the calibration phase.

The economic framework for development scenarios is limited to the calculation of direct costs of infrastructure erection. The economic model does not consider Net Present Value, Internal Rate of Return, Payback period and Weighted Average Cost of Capital concepts. Marketing expenditures and indirect costs are not included in the economic calculations.

In general, more functionality requirements to the model would require a greater number of data sources than have been used in the model.

11 LEARNING FROM THE RESEARCH

Doctoral research for a professional in his mid-forties who has only worked in a business environment is a very challenging yet absorbing learning process. This learning path is affected by contradicting life and professional factors. Firstly, having achieved a certain professional status to start again from "ground zero" and find a new equilibrium seriously shakes pre-existing comfort zones. Secondly, previous working skills, mental tools, business life hacks, managerial techniques (often surprisingly obsolete) have led to a serious professional deformation which needs to be overcome to enable the learning of academic concepts. Thirdly, as for the ability to learn and do research, personal skills and competences must be upgraded, e.g. English (especially for an international student) needs to be tuned to a new vocabulary, reading skill must be improved to enable the researcher to digest huge volumes of academic texts, writing requires a better proficiency in presenting academic theories and supporting arguments with references, and the ability to distance learning and establish a 'work-study-life' balance needs to be raised. These factors are just prerequisites for setting up a research process which leads a doctoral student through learning milestones and teaches important lessons.

11.1 Lesson 1: Understanding Philosophical Position is Genesis

Understanding a philosophical position in any phenomenon is probably the most valuable lesson from the current research affecting both professional practice and personal life. If prior to conducting the research the world was divided into "us and them", "proponents and opponents", "right and wrong", after learning the concepts of ontology and epistemology the attitude and approach towards analysing and solving practical issues have changed. Firstly, it was identified that the personal philosophical position of the researcher is based upon critical realism. The nature of the external phenomenon (scarcity of infrastructure resources) is viewed as external to a reaction (infrastructure sharing) to this phenomenon. The role of the researcher in an academic context is an external observer and reactor rather than participant. The research deliverable in the form of a software model is to generate replicable results under the same conditions. A complex system research perspective with ABM realises multivariant scenarios between factors which underlines the potential nature of causality rather than direct correlation.

Secondly, understanding others' philosophical positions towards a phenomenon demands the comprehension of deeper roots of opponents' views, helps to analyse not just the final notion but also underlying thought chains of an adversary, and therefore to develop a professional skill to accept a different opinion in an educated manner.

Thirdly, knowing different philosophical positions significantly enriched an arsenal of problem solving approaches and ability to predict outcomes. Working for an incumbent telecommunication operator requires interaction with different stakeholders, i.e. regulating authorities, competitors, consumers of telecom services. Each stakeholder has different objectives which can be clearly deconstructed and analysed from a philosophical stance and addressed on a deeper and more effective level.

11.2 Lesson 2: Changing Research Scope is Progress

Over the course of this doctoral study, all aspects of the research have changed. Problem formulation has evolved from a notion of a methodological decision making tool for regulators to the concept of a decision support software tool. The positioning study originally viewed Innovation as one of research domains which was excluded from the scope. Research questions predictably changed to reflect outcomes of research deliverables and Review Panel suggestions. Analytic Network Process (ANP) as an MCDM method was excluded from the scope of the simulation model to reflect Ofcom's requirements for infrastructure scenarios only. This subsequently led to changes in research methods, e.g. online questionnaires were excluded from data collection methods. Finally, the title of the research has changed.

Compared to professional practice with predictable execution plans and hard numerical goals, the research process appeared to be more an evolution of a living organism rather than the development plan of a product. Prior to the doctoral studies, academia was stereotypically perceived as conservative and dogmatic. An important lesson from the research is that an active researcher must be constantly open to suggestions, able to quickly abandon or adopt concepts, look for interesting opportunities, apply extant theories to analyse modern phenomena and at the same time challenge the theories from newer perspectives.

11.3 Lesson 3: Learning Java Empowers Personal Practice

Conducting research required serious upgrading of existing learning skills related to academic reading, writing, synthesising knowledge and presenting conclusions. Building the software tool also required the acquisition of a completely new skill, i.e. the ability to code in Java programming language. Although the amount of Java learnt still characterises the researcher as a beginner/intermediate, this significantly enriched professional practice. Firstly, learning a new programming language (like any new language) seriously stimulated brain activity and improved the overall ability to absorb new material. Secondly, it increased self-confidence, i.e. that learning new skills is possible at any age. Thirdly, it surprisingly added value to personal professional reputation and broadened personal networking within the organisation as the researcher gained more respect from colleagues, i.e. established managers and practising information technology professionals.

11.4 Lesson 4: Iterative Learning is a Source of Creativity

One subtle observation during the studies is the nature of creativity in academic and business worlds. In professional practice a reflective nature of creativity dominates, i.e. new ideas appear as a response to external disturbing factors or opportunities. Ironically, the best ideas were born under time pressure and serious threats. In contrast, in academic practice best ideas are taken on the basis of existing research and identifying the gap in traditional theories. Reconciliation of forward looking creativity in business and past looking creativity in academia became somewhat of a learning barrier during the initial stages of the research. New ideas for research were born with difficulty as there was limited reflection from the external environment on these ideas.

Over the course of the research, learning from iterative revision of articles read, research methods used, even own papers written became an invaluable source of new ideas. For example, during the EP, keywords from the SLR for searching electronic databases were revisited due to new conditions and new queries applied. The resulting set of new articles on the topic of infrastructure development provided new perspectives and enriched the research. The doctoral studies require the combination of problem solving and investigative skills from business and academia, i.e. quick operational issues need forward looking creativity, systemic and fundamental issues require thorough revisionist problem solving.

11.5 Lesson 5: Research Opens Doors to a New Career Path

Approaching the end of the doctoral studies raises a legitimate question on how to utilise the acquired knowledge and earned experience? Each professional with an industry background entering the academic environment faces this question. Should the researcher continue to do more part-time research and produce new academic deliverables? Or should the researcher also start teaching in a university and share accumulated business and academic experience? Or perhaps start a consulting practice where industry experience and academic knowledge mining tools can generate synergetic achievements?

The current research has planted a completely new concept of “living one more life”. Prior to the study, the career was viewed as a straightforward path upwards in primal or adjacent industry segments where personal decisions and achievements affect only the slope of the path. During the study a fear of starting a new career from scratch did not disappear but certainly became tenable. Closer to the end of the study, curiosity rises regarding the application of acquired doctorate status in a practical direction. The author of the research has already undertaken measures to start communicating with Nazarbayev University in Astana, Kazakhstan regarding a part-time teaching career.

11.6 Lesson 6: Research Expands Personal Networking

This research has significantly expanded the author’s personal networking and brought benefits to personal practice and his organisation. Every classmate in the Cranfield DBA cohort contributed practical suggestions at certain times. A classmate from California, US helped Kazakhtelecom to establish connections in Silicon Valley related to blockchain software technology. A colleague from the UK doing research in a marketing area consulted the CEO of Kazakhtelecom on certain aspects of digital marketing. A classmate from United Arab Emirates helped locally when a delegation from Kazakhtelecom visited Abu Dhabi. A classmate from Egypt helped to establish connections with the former head of ITU. As reciprocity, the author of the research consulted the Egyptian classmate on two occasions related to business fairs in Russia and Kazakhstan. A classmate from Nigeria helped to engage with the Nigerian telecom regulator to whom the current research will, potentially, be introduced. Moreover, the Cranfield lead supervisor and her staff helped the researcher to engage with academics in the UK to form the Review Panel during the SLR and engage with Ofcom to develop the simulation model during the Empirical Project. A particular lesson is that this communication over new networking channels proved to be very effective for solving issues and with high quality. Best partners promote best results.

11.7 Lesson 7: Traditional Concepts and New Phenomena Co-Evolve

Current research of IS in telecommunication required literature investigation on the historical development of infrastructures, regulation of monopolies and introduction of service- and facility-based competition. An interesting research lesson which affected both personal practice and the researcher's organisation is how traditional concepts and newer trends in network industries interact, co-evolve, challenge and fertilise each other.

A typical example of an evolving IS method in network industries is the concept of Common Carriage. Foellmi and Meister (2012) define Common Carriage as "shared use of networks, similar to telecommunication, electricity or gas" which, in the context of telecommunication, is the openness of a network to users. The development of the Internet and digital services raised the issue of Network Neutrality, which is the openness of a network to content (Hogendorn, 2007). Noam (1994) predicted that with the development of alternative operators, e.g. cable and wireless, the concept of Common Carriage from a traditional area of regulated monopolies would erode and be replaced by "neutral interconnection", a term which later became Network Neutrality. The Common Carriage provision was eliminated from the US wholesale and retail broadband services in 2002 and 2005 respectively (Cherry, 2008).

Another traditional IS method is Local Loop Unbundling (LLU), which originally was applied in copper telecommunication networks, and has also been applied and debated in relation to fibre optic networks (Cave, 2010b). This interaction of traditional concepts and new trends is also witnessed in Kazakhstan. The insights from the research help Kazakhtelecom in its communication with regulatory authorities. In terms of regulatory initiative to introduce facility-based competition, e.g. over LLU copper cables, the knowledge from the doctoral study ironically empowers the researcher's organisation to defend its historical incumbent status.

11.8 Lesson 8: Research Shows the Future

The current research provides an opportunity to study industry and regulatory trends in technologically advanced countries and provides case studies to follow or avoid for the followers. The study of network industries in developed countries provided examples of modern IS techniques, which are not witnessed yet in Kazakhstan, e.g. network virtualisation and crowdsourced infrastructure. Network virtualisation is defined as the combination of several virtual networks. i.e. "slices", residing on the same physical infrastructure (Costa-Perez *et al.*, 2013). The debate by various authors on network virtualisation and its effect on the future of mobile networks (Khan *et al.*, 2011; Zaki *et al.*, 2011; Costa-Perez *et al.*, 2013; Panchal *et al.*, 2013) empowers the researcher in formulating future strategy for Kazakhtelecom's mobile division.

The crowdsourced infrastructure paradigm with its underlying "bring your own" principle, allows the organising of a particular network on demand using public or private resources (Doyle *et al.*, 2014). Various separate owners of infrastructure elements can allocate their tangible (networks, data centres) and intangible (spectrum, software) assets to form a new network. Witnessing cases in various industries when new inventions and approaches make whole industries obsolete, this knowledge enables the researcher and his organisation to formulate preventive measures and work out defensive or collaborative strategy, e.g. offering its network elements on an IS basis, towards a crowdsourced infrastructure trend.

11.9 Lesson 9: Regional Peculiarities Affect Regulation

Studying IS and policies on a global scale suggests that various regions implement culturally different regulatory practices. The US introduced liberalisation by opening access to incumbent infrastructures. Asia Pacific countries, e.g. Korea and Japan, exercised an interventionist approach and heavily subsidised infrastructure development. Europe implemented, to some degree, a blend of liberalisation and government interventions. The SLR revealed an interesting observation, i.e. that the nature of regulation may depend less on ethnicity and more on sub-regional practices. For example, regulation on infrastructure development in Australia and New Zealand is closer to Asian practices, with a higher degree of government interventions and subsidies. This knowledge generates a better understanding of and formulating organisational responses to regulatory initiatives in Kazakhstan. After conducting the research, the regulation in Kazakhstan is clearly identified as the immediate heir of former communistic cultures with administrative regulatory practices, explaining why it still follows the footsteps of Russia even after 20 years of independence, and why the introduction of competition is such an exhausting process.

11.10 Lesson 10: Motivation and Discipline are Critical Success Factors

Part-time doctoral study is a long journey taking several years to complete. Along with learning how to manage ‘work-study-life’ balance, the research process provides a way to properly maintain motivation and discipline curves. Figure 11-1 illustrates how motivation and discipline curves changed over the four year period of research. The first year excitement is gradually fading away, especially with such deliverables as SLR and EP. An important study lesson is to monitor the motivation curve and compensate for it with constantly increasing discipline efforts. Fighting procrastination and maintaining hard discipline is vital to the overall success of research. Failure to align motivation with discipline may put a researcher off the study track and lead to risky extensions.

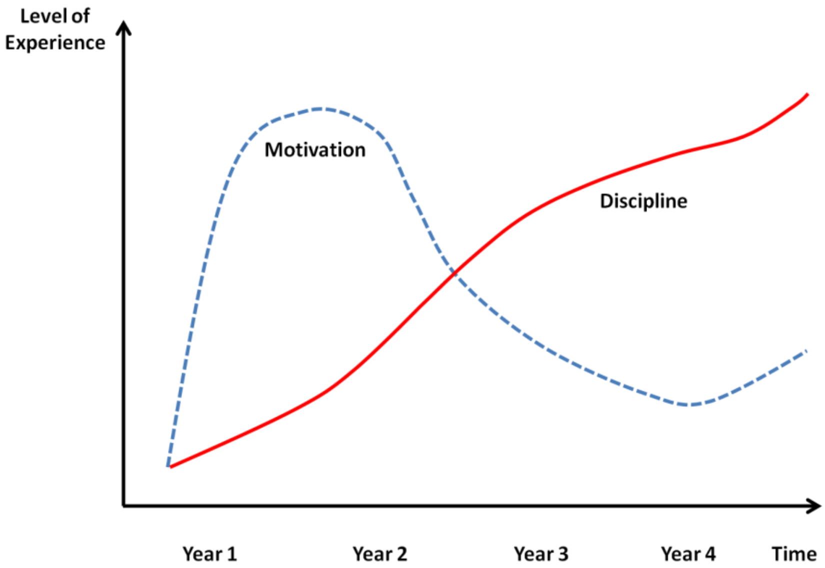

Figure 11-1 Motivation / discipline equilibrium during research

Graphics presented in Figure 11-1 are subjective and illustrate the personal learning of the author. It is possible that other researchers may experience different fluctuations in motivation but the overall lesson to maintain constant growth in academic discipline over the course of research is universal.

12 IMPLICATIONS

The outcomes of the research are of value for regulators, practitioners, representatives of telecommunication and other network industries, and scholars who deal with the topic of sustainable infrastructure development and take a complex system perspective.

The outcomes of the research are primarily addressed to NRAs. The software prototype was developed under the requirements of the UK regulator, which is viewed as a leader to follow in international telecommunication regulation. The research outcomes have the potential to attract the attention of other NRAs and have an impact on regulatory practice globally.

The software model allows scholars and academics who study the effects of mandatory network sharing on competition and infrastructure investments to analyse various network development scenarios from an ABM perspective.

The research outcomes have the potential for contribution to practice. Prospective target audiences of research outcomes are telco operators and network infrastructures. IS is becoming more popular as an intra- and inter-industry phenomenon. Consolidation of utilities leads to converged network operations, especially in underground settings. The software decision support tool can expand simulation scenarios by including sharing between utilities. A generic version of the software model tailored to the needs of consulting companies has a strong potential for commercialisation.

13 CONCLUSIONS

This study investigates Infrastructure Sharing (IS) in telecommunications as a business and regulatory strategy to enable consistent infrastructure development, satisfy growth in digital demand, address economic efficiencies and consider environmental, health and aesthetic issues of modern network industries. This thesis presents the results of the research dedicated to the topic of duct and pole access to incumbent networks and ‘bitstream’ approach.

As Jeffrey Johnson wrote in his essay *“Most of the decisions made in the modern world involve a combination of human beings and physical objects*…(and decision makers want to) *predict the behaviour of the physical subsystem, the behaviour of the human subsystem, and the emergent behaviour as the two interact and coevolve”* (Johnson, 2001). The research aims to develop a decision support tool for a National Regulating Authority (NRA) on the basis of a software simulation representing infrastructure in use as complex systems consisting of agent and infrastructure networks.

The developed simulation tool provides a solid foundation for simulating experiments, which allows the analysis of demand for Superfast and Ultrafast broadband services for different subgroups of users. This is achieved by running scenarios for new and alternative infrastructures, investigating Bitstream scenarios under different market shares, examining the influence of duct and pole availability and continuity on infrastructure development, and exploring the cost characteristics of infrastructure scenarios.

The final deliverable of the research has been created with reference to particular methodological frameworks, design concepts and approaches, selected data sources, focused attention on a particular type of IS, and a particular software development tool. All these elements have their embedded limitations which contribute to the overall quality and rigour of the final deliverable.

The software prototype, as the main outcome of the research, allows simulations and preliminary analysis of demand for broadband services, running infrastructure development scenarios for Greenfield, Brownfield and Bitstream strategies, checking space availability and path continuity in ducts and poles, studying costs of infrastructure scenarios, visualising unsatisfied demand, and customising the model functionality to obtain optional results.

The results of the study are of value for regulators, practitioners, representatives of telecommunication and other network industries and scholars who deal with the topic of sustainable infrastructure development and recognise the value of a complex system perspective.

The novelty of the research is a working software simulation tool which combines a multi method approach and views infrastructure development on the supply side in connection with an agent-based user behaviour on the demand side.

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APPENDICES

Appendix A 'List of Articles from the Positioning Study'

No.	Article	Literature Domain
1	(Abraham, 2011)	Complex Systems
2	(Ahrweiler, 2010)	Complex Systems
3	(Aksoy, 1990)	Decision Making
4	(Almond, 1987)	Business Models of Infrastructure Sharing
5	(Arrow, 1951)	Decision Making
6	(Ashby, 1957)	Decision Making
7	(Bacache, Bourreau and Gaudin, 2014)	Regulation
8	(Baldini *et al.*, 2013)	Business Models of Infrastructure Sharing
9	(Banerjee and Dippon, 2009)	Business Models of Infrastructure Sharing
10	(Barnard, 1968)	Decision Making
11	(Barrie *et al.*, 2012)	Business Models of Infrastructure Sharing
12	(Beck *et al.*, 2008)	Complex Systems
13	(Berg and Foreman, 1996)	Regulation
14	(Best, 2008)	Business Models of Infrastructure Sharing
15	(Blackman, Forge and Horvitz, 2013)	Business Models of Infrastructure Sharing
16	(Bourreau and Doğan, 2001)	Innovation
17	(Bourreau, Cambini and Hoernig, 2012)	Business Models of Infrastructure Sharing

No.	Article	Literature Domain
18	(Bourreau, Doğan and Manant, 2010)	Regulation
19	(Briglauer, Ecker and Gugler, 2012)	Regulation
20	(Brown, Beyeler and Barton, 2004)	Complex Systems
21	(Buchanan and O'Connell, 2006)	Decision Making
22	(Cadman, 2010)	Business Models of Infrastructure Sharing
23	(Cambini and Jiang, 2009)	Regulation
24	(Cambini and Silvestri, 2013)	Business Models of Infrastructure Sharing
25	(Carlsson, 2006)	Innovation
26	(Carlsson *et al.*, 2002)	Innovation
27	(Castellacci, 2006)	Innovation
28	(Cave, 2006)	Regulation
29	(Cave, 2010a)	Business Models of Infrastructure Sharing
30	(Cave, 2010b)	Regulation
31	(Cave and Webb, 2012)	Business Models of Infrastructure Sharing
32	(Chaminade, Intarakumnerd and Sapprasert, 2012)	Innovation
33	(Chang, Koski and Majumdar, 2003)	Regulation
34	(Chappin and Dijkema, 2010)	Complex Systems
35	(Charnes, Cooper and	Decision Making

No.	Article	Literature Domain
	Ferguson, 1955)	
36	(Cohen and Southwood, 2008)	Business Models of Infrastructure Sharing
37	(Cohon, 1978)	Decision Making
38	(Crandall, Eisenach and Ingraham, 2013)	Business Models of Infrastructure Sharing
39	(Criner, 1977)	Business Models of Infrastructure Sharing
40	(Dantzig, 2002)	Decision Making
41	(Daoud, Alanyali and Starobinski, 2013)	Business Models of Infrastructure Sharing
42	(Dassler, 2006)	Regulation
43	(Davidson, 1987)	Innovation
44	(De Finetti, 1937)	Decision Making
45	(De Streel, 2008)	Regulation
46	(Deshpande, 2013)	Business Models of Infrastructure Sharing
47	(Dillon, 2001)	Complex Systems
48	(Dobson *et al.*, 2007)	Complex Systems
49	(Durantini and Martino, 2013)	Business Models of Infrastructure Sharing
50	(Economides and Tåg, 2012)	Regulation
51	(Edgeworth, 1881)	Decision Making
52	(Edquist and Hommen, 1999)	Innovation
53	(Edwards, 1954)	Decision Making
54	(Egan, 1990)	Business Models of Infrastructure Sharing

No.	Article	Literature Domain
55	(Egan, 1988)	Regulation
56	(Fabrizi and Wertlen, 2008)	Business Models of Infrastructure Sharing
57	(Fagerberg and Srholec, 2008)	Innovation
58	(Farquhar and Fitzgerald, 2003)	Business Models of Infrastructure Sharing
59	(Fishburn, 1970)	Decision Making
60	(Flacher and Jennequin, 2008)	Regulation
61	(Foreman-Peck, 1985)	Regulation
62	(Forge and Blackman, 2006)	Business Models of Infrastructure Sharing
63	(Forrester, 1961)	Complex Systems
64	(Foster, 2008)	Business Models of Infrastructure Sharing
65	(Freeman, 1989)	Innovation
66	(Freeman, 2002)	Innovation
67	(Frisanco *et al.*, 2008)	Business Models of Infrastructure Sharing
68	(Frisch, 1926)	Decision Making
69	(Gabel, 2007)	Regulation
70	(Gallouj and Zanfei, 2013)	Innovation
71	(Garcia-Murillo and MacInnes, 2001)	Regulation
72	(Gencer and Gürpinar, 2007)	Decision Making
73	(Gillick, 1992)	Regulation

No.	Article	Literature Domain
74	(Ginzberg and Stohr, 1982)	Decision Making
75	(Giokas and Pentzaropoulos, 2008)	Decision Making
76	(Goicoechea, Hansen and Duckstein, 1982)	Decision Making
77	(Gómez-Barroso and Feijóo, 2010)	Regulation
78	(Grinin, Devezas and Korotayev, 2012)	Innovation
79	(Grove and Baumann, 2012)	Complex Systems
80	(GSMA, 2010)	Business Models of Infrastructure Sharing
81	(Gulati and Yates, 2012)	Regulation
82	(Harris, 1990)	Innovation
83	(Hart, Reed and Bar, 1992)	Innovation
84	(Hazlett, 2003)	Business Models of Infrastructure Sharing
85	(Hazlett, 2006)	Regulation
86	(Hazlett, 1986)	Regulation
87	(Hekkert *et al.*, 2007)	Innovation
88	(Hemphill, 2013)	Innovation
89	(Herder, Bouwmans and Dijkema, 2008)	Complex Systems
90	(Hermens, 1941)	Innovation
91	(Higham, 1994)	Business Models of Infrastructure Sharing
92	(Higham, 1993)	Business Models of Infrastructure Sharing

No.	Article	Literature Domain
93	(Ho, 2008)	Decision Making
94	(Holland, 1998)	Complex Systems
95	(Holland, 1995)	Complex Systems
96	(Holt and Galligan, 2013)	Regulation
97	(Horne, 2013)	Regulation
98	(Huigen and Cave, 2008)	Regulation
99	(Infante and Vallejo, 2012)	Business Models of Infrastructure Sharing
100	(Irwin and Ela, 1981)	Regulation
101	(Jayakar, 1999)	Regulation
102	(Johnson, 1986)	Regulation
103	(Jorswieck *et al.*, 2010)	Business Models of Infrastructure Sharing
104	(Joskow and Noll, 1981)	Regulation
105	(Kahneman and Tversky, 1979)	Decision Making
106	(Katz, 2006)	Innovation
107	(Keeney and Raiffa, 1976)	Decision Making
108	(Kiessling and Blondeel, 1998)	Regulation
109	(Knight, 1921)	Decision Making
110	(Köksalan, Wallenius and Zionts, 2013)	Decision Making
111	(Koopmans, 1951)	Decision Making
112	(Korotayev, Zinkina and	Innovation

No.	Article	Literature Domain
	Bogevolnov, 2011)	
113	(Lazauskaite, 2008)	Business Models of Infrastructure Sharing
114	(Lebourges, 2010)	Regulation
115	(Lefèvre, 2008)	Business Models of Infrastructure Sharing
116	(Levin, 1982)	Business Models of Infrastructure Sharing
117	(Levin, 2010)	Regulation
118	(Lundvall, 1992)	Innovation
119	(Madden and Savage, 1999)	Innovation
120	(Majumdar, 1992)	Regulation
121	(Maleki and Zahir, 2013)	Decision Making
122	(McDaniel, 2000)	Innovation
123	(McLauchlan and Westerberg, 1982)	Business Models of Infrastructure Sharing
124	(McMillan, 1995)	Business Models of Infrastructure Sharing
125	(Meisel, 1992)	Business Models of Infrastructure Sharing
126	(Melody, 1999)	Regulation
127	(Metcalfe, 1994)	Innovation
128	(Milano and Lombardi, 2014)	Decision Making
129	(Mitchell, 1998)	Complex Systems
130	(Mudd and Starkey, 1992)	Business Models of Infrastructure Sharing
131	(Nelson, 1993)	Innovation
132	(Nelson and Winter, 1977)	Innovation
133	(Newman, 2010)	Complex Systems

No.	Article	Literature Domain
134	(Nicolis and Prigogine, 1989)	Complex Systems
135	(Nikou and Mezei, 2013)	Decision Making
136	(Nilsson and Darley, 2006)	Complex Systems
137	(Noam, 2010)	Regulation
138	(OECD, 1997)	Innovation
139	(Onishi and Tsuna, 2010)	Regulation
140	(Opricovic, 1998)	Decision Making
141	(Papenhausen, 2008)	Innovation
142	(Patel and Pavitt, 1994)	Innovation
143	(Peha, 2013)	Business Models of Infrastructure Sharing
144	(Posner, 1974)	Regulation
145	(Quer *et al.*, 2012)	Business Models of Infrastructure Sharing
146	(Raiffa, 1969)	Decision Making
147	(Raiffa, 1968)	Decision Making
148	(Ramsey, 1931)	Decision Making
149	(Regli, 1996)	Business Models of Infrastructure Sharing
150	(Renda, 2010)	Business Models of Infrastructure Sharing
151	(Rigopoulos and Psarras, 2007)	Decision Making
152	(Rinaldi, Peerenboom and Kelly, 2001)	Business Models of Infrastructure Sharing
153	(Roy, 1968)	Decision Making
154	(Russo and Rossi, 2009)	Complex Systems

No.	Article	Literature Domain
155	(Saaty, 2007)	Decision Making
156	(Saaty, 1996)	Decision Making
157	(Saaty, 1977)	Decision Making
158	(Schaffer and Grefenstette, 1985)	Decision Making
159	(Schiller, 1998)	Regulation
160	(Schneir and Xiong, 2013)	Business Models of Infrastructure Sharing
161	(Schorr, 2008)	Business Models of Infrastructure Sharing
162	(Sharif, 2006)	Innovation
163	(Shin and Bartolacci, 2007)	Business Models of Infrastructure Sharing
164	(Shin, 2010)	Business Models of Infrastructure Sharing
165	(Silverberg, 2005)	Innovation
166	(Simon and Barnard, 1947)	Decision Making
167	(Sipahi and Timor, 2010)	Decision Making
168	(Snow, 1988)	Regulation
169	(Solomon, 1978)	Regulation
170	(Song, Zo and Lee, 2012)	Regulation
171	(Stern, 2004)	Regulation
172	(Stylianou, 2011)	Innovation
173	(Subramanian and Ramanathan, 2012)	Decision Making
174	(Sweeney and Griffiths, 2002)	Complex Systems
175	(Tang, 2006)	Innovation

No.	**Article**	**Literature Domain**
176	(Teece, 1992)	Innovation
177	(Ting, Wildman and Bauer, 2005)	Business Models of Infrastructure Sharing
178	(Toossi, Camci and Varga, 2013)	Decision Making
179	(Tran *et al.*, 2014)	Business Models of Infrastructure Sharing
180	(Treasury, 2013)	Business Models of Infrastructure Sharing
181	(Valletti, 2003)	Regulation
182	(Valletti and Cave, 1998)	Business Models of Infrastructure Sharing
183	(Van Cuilenburg and Slaa, 1995)	Innovation
184	(Van Cuilenburg and Slaa, 1994)	Innovation
185	(Van Duijn, 1981)	Innovation
186	(Varga *et al.*, 2014)	Complex Systems
187	(Velasquez and Hester, 2013)	Decision Making
188	(Von Neumann and Morgenstern, 1944)	Decision Making
189	(Von Winterfield and Edwards, 1986)	Decision Making
190	(Waldrop, 1993)	Complex Systems
191	(Waverman and Koutroumpis, 2011)	Regulation
192	(Webb, 2008)	Business Models of Infrastructure Sharing

No.	Article	Literature Domain
193	(Weber and Rohracher, 2012)	Innovation
194	(Wenders, 1990)	Regulation
195	(Wenders, 1988)	Regulation
196	(Wonglimpiyarat, 2005)	Innovation
197	(Wyman, 2007)	Business Models of Infrastructure Sharing
198	(Yang *et al.*, 2013)	Regulation
199	(Yang, Shieh and Tzeng, 2009)	Decision Making
200	(Yoon and Kinoshita, 2010)	Decision Making
201	(Ypsilanti, D., Xavier, 1998)	Regulation
202	(Zanakis, Evans and Vazacopoulos, 1989)	Decision Making
203	(Zanfei, 1993)	Innovation
204	(Zia and Koliba, 2013)	Decision Making

Appendix B Shortlist of 61 articles selected for SLR after quality appraisal

Ref No	Citation details
1	(Cave, 2008)
2	(Wright and Cave, 2011)
3	(Foellmi and Meister, 2012)
4	(Saal *et al.*, 2013)
5	(Sawkins, 2001)
6	(Stern, 2012)
7	(Brunekreeft, 1997)
8	(Growitsch and Stronzik, 2014)
9	(Santa and Sikora, 2004)
10	(Lassila *et al.*, 2009)
11	(Malmendier and Schendel, 2006)
12	(Mogel and Gregg, 2004)
13	(Newbery, 2005)
14	(Pollitt, 2008)
15	(Bartlett and Jackson, 2002)
16	(Berkers *et al.*, 2010)
17	(Biggar, 2003)
18	(Bittlingmayer and Hazlett, 2002)
19	(Blackman, Forge and Horvitz, 2013)
20	(Bourreau and Doğan, 2005)
21	(Bublin and Causevic, 2008)

22	(Cave, 2010b)
23	(Cave, 2014)
24	(Costa-Perez *et al.*, 2013)
25	(Crandall, 2005)
26	(Crandall, Eisenach and Ingraham, 2013)
27	(Day, 2002)
28	(Doyle *et al.*, 2014)
29	(Falch, Henten and Tadayoni, 2009)
30	(Frisanco *et al.*, 2008)
31	(Gabelmann, 2001)
32	(Hausman and Sidak, 1999)
33	(Hazlett, 2006)
34	(Hogendorn, 2007)
35	(Infante and Vallejo, 2012)
36	(Chatzicharistou, 2010)
37	(Khan *et al.*, 2011)
38	(Meddour, Rasheed and Gourhant, 2011)
39	(Noam, 1994)
40	(Offergelt, 2011)
41	(Onishi and Tsuna, 2010)
42	(Panchal, Yates and Buddhikot, 2013)
43	(Shin and Bartolacci, 2007)
44	(Soares and Sarmento, 2012)

45	(Song, Zo and Lee, 2012)
46	(Song, Zo and Ciganek, 2014)
47	(Wallsten and Hausladen, 2009)
48	(Zaki *et al.*, 2011)
49	(Cherry, 2008)
50	(Drew, 2009)
51	(Hummer *et al.*, 2006)
52	(Levinson, 2009)
53	(Marvin and Slater, 1997)
54	(Morris *et al.*, 2009)
55	(Parsons *et al.*, 2014)
56	(Resor, Hickey and Trb, 2005)
57	(Inderst and Peitz, 2012)
58	(Bourreau, Cambini and Hoernig, 2012)
59	(Karvetski, Lambert and Linkov, 2009)
60	(Boggia and Rocchi, 2010)
61	(Walker, 2000)

Appendix C Quality appraisal form of and rationale for a rejected article

Excluded Article 1	
Citation Brunner, N. and Starkl, M., (2012), "Financial and Economic Determinants of Collective Action: The Case of Wastewater Management", *Environmental Impact Assessment Review*, Volume *32,* Issue 1, pp. 140–150	
Authors: (Brunner and Starkl, 2012) **Title:** Financial and Economic Determinants of Collective Action: The Case of Wastewater Management	
Quality Criteria	**Quality score** **(1 lowest to 5 highest)**
Is the objective of the article rightly aligned with the objectives of my SLR? Specifically, does the article address regulatory decision making in respect of IS and joint use of public facilities?	2
Is the research question of the article clearly formulated? Is it aligned with any of this SLR questions (SubQ1, SubQ2, SubQ3 or MainQ)	3 2
Is the review of relevant literature presented in the article?	4
Does the paper present a clear methodology of research, data collection, sampling and analysis?	4
Are the findings explicitly formulated?	3
Does the discussion answer the research question and objectives of the paper?	3
What is the overall quality of the paper and its contribution	3

to knowledge? What is the impact factor of the Journal? What is SJR ranking of the Journal?	2.05 1.22
Total Score (the range is from 8 to 40+)	27.27
Was the paper selected (if total score more than 28)	**No**
Comments if not selected This article is about funding and specifically about cost sharing in building sewerage systems in developing and developed countries. Not about actual infrastructure sharing.	

Appendix D Example of a Data Extraction Form

Ref No 1
Citation (Cave, 2008)
Title: Independent Review of Competition and Innovation in Water Markets: Final Report
Author(s): Cave, M.
Journal/Source: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69462/cave-review-final-report.pdf
Year: 2008
Keywords: Water markets, Competition, Innovation
Study Background
Research Question / Purpose of paper: “to recommend changes to the frameworks of the industry to deliver benefits to customers and the environment”
Primary Research Focus: Introduction of competition in the Water industry of England and Wales
Grounding Literature: Various UK agencies reports
Methodology
Method: Empirical: An integrated approach to analyse costs and benefits of greater use of competition, the adoption of market-like instruments and the reform of monopoly regulation
Data Description: Data from UK and Wales national statistics, environmental and other agencies
Data Collection Instrument
Sector: Water
Unit of Analysis: National level of England and UK

Analytical approach: Analysis of current situation in water industry, collecting responses from stakeholders
Type of Infrastructure Sharing: Open access, Common carriage, Rights-of-Way
Contribution
Key findings: Recommended reforms in water abstraction, resources, treatment, infrastructure, mergers regime, creation of an R&D agency
Key propositions and arguments: Introduce reforms in England and Wales water industries where risk-reward ratio is the most appropriate to avoid ‘one-size-fits-all’ approach
Limitations and Scope for further research: General overview of water industry with no particular focus on Infrastructure sharing methods
Synthesis/Key contribution to review question(s): Open access and Common Carriage models are considered in relation to market reforms

Appendix E ‘Testimony from Kazakhstani Regulator’

ҚАЗАҚСТАН РЕСПУБЛИКАСЫ АҚПАРАТ ЖӘНЕ КОММУНИКАЦИЯЛАР МИНИСТРЛІГІ “БАЙЛАНЫС, АҚПАРАТТАНДЫРУ ЖӘНЕ БҰҚАРАЛЫҚ АҚПАРАТ ҚҰРАЛДАРЫ САЛАСЫНДАҒЫ МЕМЛЕКЕТТІК БАҚЫЛАУ КОМИТЕТІ” РЕСПУБЛИКАЛЫҚ МЕМЛЕКЕТТІК МЕКЕМЕСІ

МИНИСТЕРСТВО ИНФОРМАЦИИ И КОММУНИКАЦИЙ РЕСПУБЛИКИ КАЗАХСТАН РЕСПУБЛИКАНСКОЕ ГОСУДАРСТВЕННОЕ УЧРЕЖДЕНИЕ “КОМИТЕТ ГОСУДАРСТВЕННОГО КОНТРОЛЯ В ОБЛАСТИ СВЯЗИ, ИНФОРМАТИЗАЦИИ И СРЕДСТВ МАССОВОЙ ИНФОРМАЦИИ”

010000, Астана қаласы, Есіл ауданы, Министрліктер үйі, Мәңгілік ел, 8 үй, 14 кіреберіс, тел.: 8 (7172) 74-03-02, факс: 8(7172) 74-03-64 e-mail: mic@mic.gov.kz

010000, город Астана, Есильский район, Дом министерств, Мәңгілік ел, дом 8, подъезд 14, тел.: 8 (7172) 74-03-02, факс: 8(7172) 74-03-64 e-mail: mic@mic.gov.kz

№ 16-01-16-2/1305-И

18.04.2017г.

To Whom It May Concern

From State Control Committee
in the Sphere of Communication, Informatization
and Media Ministry of Information and
Communication Republic of Kazakhstan

Dear Sirs,

We would like to thank Mr. Yerlan Durmagambetov, Managing Director of JSC Kazakhtelecom, for presenting his doctoral research “A Complex Systems Perspective on Innovation, Investment and Regulation of Evolving Telecommunication Networks”. This research is dedicated to Infrastructure Sharing in telecommunication which is in the list of very actual topics now in Kazakhstan from the regulatory point of view.

The issues of spectrum sharing, mobile virtual network operatorship, tower and mast sharing are now on today’s agenda of Kazakhstani telecom regulator.

It was interesting to find out from Mr. Durmagambetov’s research that development of modern broadband fiber networks with respect of duct and pole sharing can be presented in a computer simulation model. Agent Based Modeling for picturing behavioral strategies of users, incumbent and alternative operators and their influence on infrastructure development is a novel research perspective to current issues in telecommunication segment. Also, initiatives of the UK regulator Ofcom for stimulating alternative operators to develop own physical networks were of particular interest.

The doctoral research of Mr. Durmagambetov coincides with our initiatives in the sphere of infrastructure sharing. The outcomes of his research and expertise can be used in our projects in the future. The exact form of Mr. Durmagambetov’s involvement will be defined upon special requirements of a particular matter.

Best regards
Chairman **A. Kozhikhov**

000443

Appendix F ‘Testimony from the BO of the RCC’

REGIONAL COMMONWEALTH IN THE FIELD OF COMMUNICATIONS

EXECUTIVE COMMITTEE

7, Tverskaya Str., Moscow 125375, Russian Federation
Tel: +7 495 692 71 34. Fax: +7 495 692 70 43 E-mail: ecrcc@rcc.org.ru www.rcc.org.ru

To: Cranfield University
School of Management
Bedfordshire, UK

From: Executive Committee
Regional Commonwealth in the field of Communications
Moscow, Russia

Dear Sirs,

We are writing this letter in regard of Mr. Yerlan Durmagambetov’s doctoral study “A Complex Systems Perspective on Innovation, Investment and Regulation of Evolving Telecommunication Networks”.

Mr. Durmagambetov is Managing Director of JSC Kazakhtelecom. Kazakhtelecom is a member of Board of Operators of the Regional Commonwealth in the field of Communications (RCC) which is an official entity of International Telecommunication Union. Currently, the Chairman of Kazakhtelecom is also Chairman of the Board of Operators. Mr. Durmagambetov is responsible for coordination of work between Kazakhtelecom and the RCC.

We have been following the development of Mr. Durmagambetov’s research in the area of infrastructure sharing since his enrollment to doctorate programme. We confirmed our professional interest in and supported the topic of infrastructure sharing in 2013 when the research proposal was formulated. We get acquainted with the first version of software simulation in 2016. We also witnessed in April 2017 how this model has progressed.

During this time Mr. Durmagambetov’s raised initiatives on focused development of the topic of infrastructure sharing within the Board of Operators. After second presentation of his doctoral studies in Minsk, Belarus in 2017 we may consider running a pilot project dedicated to outsourcing of telecommunication services from an operator’s perspective. We would like to apply his research approach to an operator who does not have own physical infrastructure but shares it from various infrastructure providers and coordinates interactions and resource allocation among them.

The outcomes of Mr. Durmagambetov’s research are of significant interest to us and can generate practical impact on our future work.

N. Mukhitdinov
Director General

Appendix G ‘Electronic Version of Simulation Model’

The electronic version of the software model is exported from AnyLogic simulation environment into Java-based platform independent executable files and recorded onto DVDs (available as attachment to the hard copy of this Thesis from Cranfield library).