Fixed Telecom Access:
Full Fibre Cost Modelling

Model Report

June 2019

Prepared for:

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1 Introduction

1.1 Ofcom commissioned Cartesian to build a bottom-up network cost model ('the network cost model') to estimate the cost of deploying full-fibre services in the UK.

1.2 This document provides an overview of Cartesian's implementation of Version 1 of the network cost model. It should be noted that the network dimensioning parameters and cost inputs contained in this version of the model are placeholder values and are only included to allow Ofcom to consult with a functioning model.

1.3 An updated version of the model will be published in light of stakeholder views to Version 1 of the model and input assumptions informed by Communication Providers' data.

2 Document Structure

2.1 This document provides an overview of the network cost model:

- Section 1 provides an introduction to the project;
- Section 2 outlines the document structure;
- Section 3 presents the scope of the model;
- Section 4 summarises the technologies in scope;
- Section 4 details the model structure;
- Section 6 describes the Geospatial analysis methodology;
- Section 7 describes the approach for the Infrastructure module;
- Section 8 describes the approach for the Network module; and
- Section 9 describes the implementation of the Cost module.

3 Scope

Services in Scope

3.1 The network cost model has five residential and business services in scope:

- Fibre to the Premises (FTTP);
- Ethernet Leased Line;
- Dark Fibre;
- Optical Services; and
- Ducts and Pole Access (DPA).

3.2 The underlying technologies supporting these services are explained in detail in Section 4 (*Technologies in Scope*).

Geographic Coverage

3.3 The geographic scope of the network cost model covers the entire UK except for the Hull area.

3.4 Subnational network deployments can be modelled through choice of deployment scenario, which is an input to the network cost model.

3.5 In its December 2018 Consultation, Ofcom proposed grouping postcode sectors in the UK into three Geographic Areas according to the levels of network competition (or potential for network competition). In section 4 we explain how these Geographic Areas are used in the model.

Geographic Units

3.6 Postcode sectors are used as the indivisible unit when modelling a coverage rollout, i.e. a deployment scenario will include either the whole postcode sector or none of it. The benefits of using postcode sectors are two-fold:

- Postcode sectors provide a good balance between granularity and data management limitations: the input data provided by Ofcom shows that the UK premises for which we have location data are distributed across c.9,600 postcode sectors, with an average of c.3,000 premises each.
- Ofcom is proposing to use postcode sectors as the geographic unit to analyse the Geographic Areas; therefore, using the same unit provides consistency with Ofcom's analysis.

3.7 The construction costs to install underground ducts are driven largely by the surface type, for example soft ground, pavement and carriageway. The network cost model categorises Exchanges into eight geotypes (Exchange Geotypes) each having a defined surface type mix. The model uses surface-type mix input data for each geotype to estimate construction costs.

3.8 Postcode sectors are assigned to the geotype of the Exchange that serves them (where more than one Exchange serves the postcode sector, the Exchange connecting the majority of premises is selected). Each geotype has a different surface type mix for each network segment (see paragraph 4.2 for the definition of network segments in the model).

Network Optimisation

3.9 The model supports two network optimisation approaches: scorched node and scorched earth.

3.10 The scorched node approach assumes the reuse of existing copper cabinet and Exchange locations for the installation of the relevant network equipment (e.g. FTTP splitter nodes at the copper cabinets – see Figure 2 for details on the FTTP technology). This approach is aimed at modelling how the reutilisation of existing passive physical infrastructure routes (e.g. ducts, poles, footway boxes) would affect the overall network costs.

3.11 The scorched earth approach assumes an alternative design and topology so as to minimise total length of the physical passive infrastructure (e.g. ducts and poles). In scorched earth, the network equipment is not constrained by the location of current copper cabinets and exchanges. More details of the geospatial approach for each topology can be found in Section 6.

3.12 The model contains a worksheet with a set of input parameters which represent the amount of existing physical passive infrastructure (e.g. ducts, footway boxes) which will be re-used as opposed to newly built. The user of the model can determine if these parameters should have different values for the two network optimisation approaches, scorched node and scorched earth.

Timeframe

3.13   Time periods in the analysis are financial years (FY), i.e. 1st April to 31st March. The Model covers a period of 40 years with an option to set the start year.

4   Technologies in Scope

Network Section in Scope

4.1   The analysis models the access network, e.g. from the Access Node (Exchange) to the premises, for all the services in scope (Fibre-To-The-Premises, Ethernet and Optical Leased Lines, Dark Fibre and, Duct and Pole Access). The model also covers a portion of the backhaul segment, specifically the inter-Exchange fibre connections to deliver dedicated Business services (e.g. Leased Lines, Dark Fibre).

Figure 1.   *Network Sections in Scope*
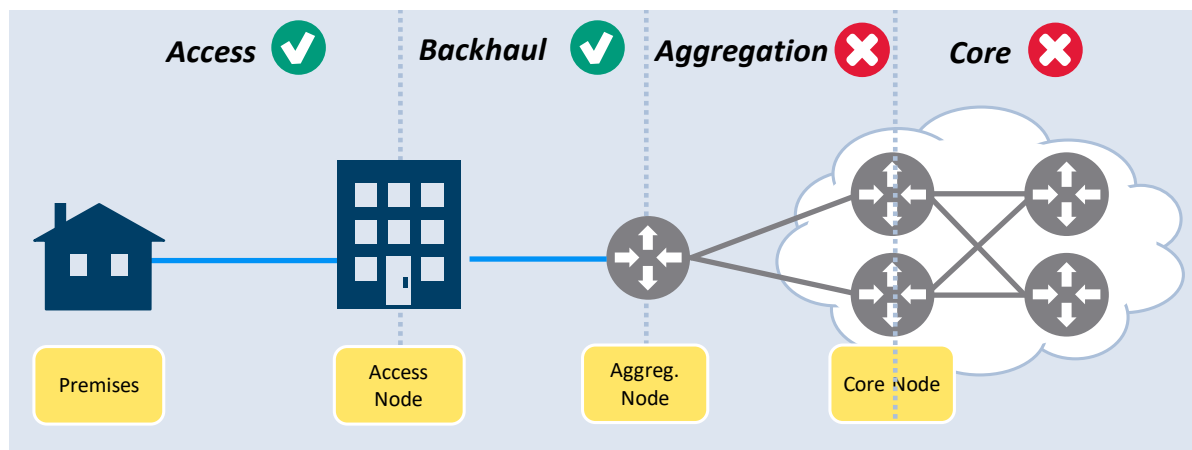
Source: Cartesian

FTTP

Technology Overview

4.2   FTTP is a broadband access technology where fibre is used end-to-end from the exchange to the premises. We model FTTP with PON (Passive Optical Network) technology. The figure below shows the FTTP physical network architecture in scope for the model across the different network segments[1]:

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[1] Segment 1: between the Exchange (or Fibre Node) and the Splitter Node; Segment 2: between the splitter node and the Distribution Point; and Segment 3: between the Distribution Point and the Customer Premises

Figure 2. *Access Network: FTTP PON High-Level Physical Architecture*
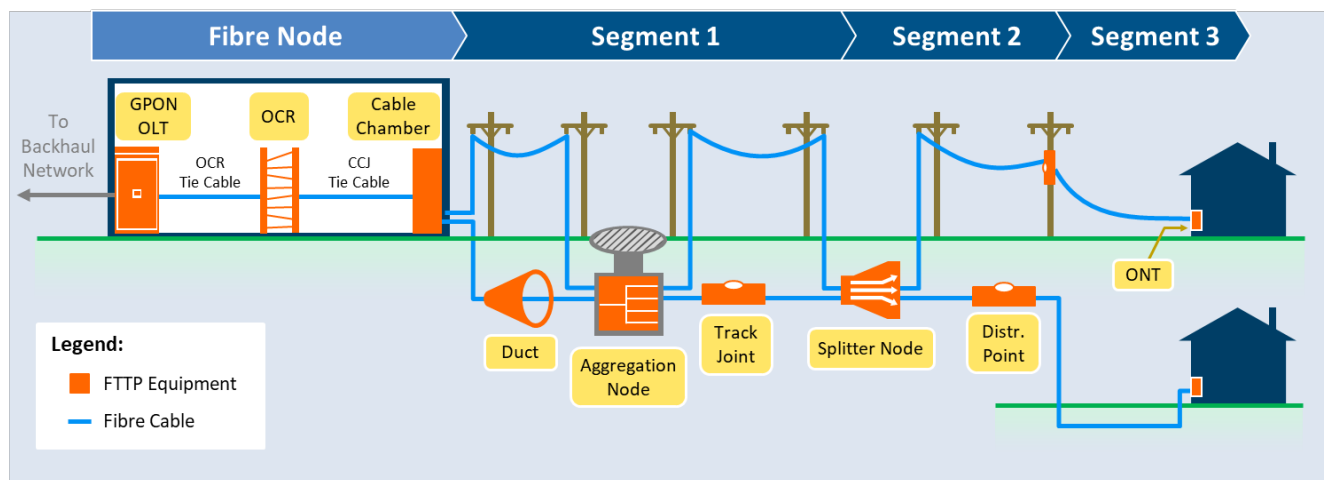
Source: Cartesian

4.3 The main benefits of using an FTTP PON topology are 1) there is no need for active components between the exchange and the premises, and 2) multiple subscribers share the same fibre at Segment 1 thereby reducing the number of ports required at the Fibre Node.

4.4 Operators in the real world may use either a single splitter between the Exchange and the premises, or multiple splitters (usually two), known as cascaded splitters. To simplify the model we have assumed the single splitter approach throughout. While the Single-splitter approach may have higher fibre costs it will have lower splitter node and footway box costs.

4.5 The following split ratios are used in the model:

- Split ratio of 1:16 in those postcode sectors in Geographic Area 3 with long fibre lengths[2]. The rationale is that the signal to remote premises would be too weak if a larger split ratio was used;
- Split ratio of 1:32 as default for the remainder of premises[3].

4.6 With regards to PON capacity, GPON (supporting a total of 2.5Gbps downstream and 1.25Gbps upstream per port), is the most prevalent technology currently deployed worldwide. However, in the 40-year timespan of the model, it is reasonable to expect that network operators will deploy higher-capacity versions of PON, e.g. 10G-PON, as bandwidth demand grows over time. The model captures these dynamics as follows:

- The unit cost of the GPON equipment is adjusted over time to reflect the transition from GPON to future variants, such as 10G-PON. Specifically, the model assumes the GPON / 10G-PON mix changes from GPON-only in year 1, to 10G-PON-only in year 10. The same logic is applied to the unit cost of ONTs (Optical Network Terminal) at the customer premises. The rest of the network components (e.g. the splitter node) are passive, therefore do not need adjusting.

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[2] In the draft version of the model we have set the threshold to 32km.
[3] The Openreach 'Upgrading the Access Network with FTTP' consultation, July 2017, proposed to use centralised 32-way splitters.

- Efficiencies from the transition to higher capacity PON equipment are accounted for by not allowing the number of PON equipment to vary with bandwidth demand. Instead, the number of PON equipment is determined by coverage and take-up. Therefore, the underlying assumption is that, as bandwidth demand grows, GPON equipment is replaced with 10G PON equipment rather than through additional units of GPON equipment being installed.

Network Elements

4.7   The table below summarises the network components considered for the FTTP deployment.

Figure 3.   ***FTTP List of Network Components***

Element	Description
GPON OLT (Chassis, South-bound and North-bound Cards)	A GPON Optical Line Termination (OLT) aggregates the signals from the FTTP subscribers. The model has three subcomponents: • OLT Chassis: The housing that hosts the Network Cards and any common equipment cards not listed below (e.g. fan tray, power module) • OLT Southbound card: Network card containing the GPON ports, facing the access network • OLT Northbound card: Network card carrying aggregated traffic, facing the backhaul network
Tie Cables at the Exchange (CCJ and OCR)	There are two types of tie cables at the Fibre Node • The CCJ_Tie Cable extends the Segment 1 fibre from the Cable Chamber to the OCR • The OCR_Tie Cable connects the OLT to the OCR
OCR (Chassis, Sub-rack)	The Optical Consolidation Rack (OCR) connects the OCR Tie Cable into fibre cables for direct connection to the active equipment (in this case, the OLT). The OCR is an efficient alternative to the traditional Optical Distribution Frame (ODF). The model splits the OCR into two sub-components: • OCR Chassis: Metal cabinet enclosure to host the OCR sub-racks • OCR Sub-racks: The sub-rack slots into the rack, and is used to facilitate the fibre connections
Cable Chamber Joint	Situated at the entrance of the Fibre Node, the cable chamber aggregates the fibre cables from Segment 1 and interconnects with the OCR Tie Cable
Exchange Accommodation	Following a similar approach to that used by Cartesian in the WLA market review[4], we propose to estimate an aggregated average capital cost per rack of active equipment at the Exchange, which will include the loaded cost of items such as AC/DC power equipment (not electricity use), air conditioning equipment, security, alarm systems, etc.
Segment 1 FTTP Fibre (OH and UG)	Fibre cable between the Exchange and the Splitter Node. This segment can be Aerial or Underground. The draft model uses cables of 36 fibres for the FTTP deployment. Every fibre has an associated *fibre testing* cost, which is captured in a separate cost component. The length of FTTP fibre cable in Segment 1 at each postcode sector is calculated by the Geospatial analysis (see Section 6 for more details). The network cost model aggregates the total number of fibres required each year, using the postcode sectors enabled each year as per the coverage matrix (see 5.4 for more details).

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[4] Paragraphs 3.39 – 3.40 of the Annex 29 of Ofcom's WLA Final Statement

Segment 1 Aggregation Node and Track Joint (Footway Box and Equipment)	Passive elements to aggregate and distribute the fibre from the Exchange to the Splitter Node. We assume the Aggregation Node to be always underground and Track Joints to be located underground and overhead. Footway Boxes are modelled as separate components. The rationale is two-fold: • It allows the model to assign different asset lives for the footway box (street civils) and the equipment (Optical Passive Equipment). • As explained in 3.12, the network cost model has a set of input parameters which represent the amount of existing physical passive infrastructure to be used. There is a specific parameter which sets the share of Segment 1 Footway Boxes which need to be newly built; the model assumes that the remainder footway boxes are not required to be built, as the passive equipment (Aggregation Nodes, Track Joint) can be housed in existing infrastructure.
Segment 2 Splitter Node (Footway Box and Equipment)	The optical splitter allows a single PON interface to be shared among a number of subscribers. The splitter ratios used in the network cost model are covered in paragraphs 4.4 - 4.5. The model assumes all Splitter Nodes to be underground. As per paragraph 3.12, and the explanation above, the model has a specific parameter for the share of Segment 2 Splitter Node Footway Boxes which need to be newly built; the model assumes that the remainder footway boxes are not required to be built, as the passive equipment (Splitter Node) can be housed in existing infrastructure.
Segment 2 FTTP Fibre (OH and UG)	Fibre cable between the Splitter Node location and the Distribution Point. This segment can be Aerial or Underground. The draft model uses cables of 36 fibres for the FTTP deployment. Every fibre has a *fibre testing* cost associated, which is captured in a separate cost component. The length of FTTP fibre cable at Segment 2 uses the same approach as Segment 1, i.e. calculated by the geospatial analysis for each postcode sector and aggregated in the cost model using the coverage deployment matrix.
Segment 2 Distribution Point (Footway Box and Equipment)	The Distribution Point (DP) is where the Segment 2 cables terminate for connection to the drop cables (Segment 3). This component can be Aerial or Underground. As per section 3.12, the model has a specific parameter for the share of underground Segment 2 DP Footway Boxes which need to be newly built; the model assumes that the remainder footway boxes are not required to be built, as the passive equipment (DP) can be housed in existing infrastructure.
Segment 3 Fibre (OH and UG)	Fibre cable between the Distribution Point at street level, and the ONT at the customer premises. This segment can be Aerial or Underground. We use a 1-fibre cable for this segment. Every fibre has a *fibre testing* cost associated, which is captured in a separate cost component. FTTP Fibre at Segment 3 is modelled to be required for every FTTP service provision. The Geospatial Analysis calculates an average length of fibre per premises for each postcode sector. The network cost model uses this input value and the coverage deployment matrix to calculate the weighted average length of fibre at Segment 3 for each year of the model.
Segment 3 ONT (Connection Civils and Equipment)	The Optical Network Terminal (ONT), located in the customer premises, terminates the GPON network and presents an Ethernet interface to the customer. The ONT is connected to the Customer Premises Equipment (CPE). The model also includes a separate component for the civils work required to install the ONT

Source: Cartesian

4.8　In addition to the elements above, FTTP also uses passive infrastructure (ducts, poles, microtrench and sub-ducts) which is shared by all services. These components are explained in the Infrastructure Module, in section 7.

Ethernet Leased Lines

Technology Overview

4.9   An Ethernet fibre leased line is a point-to-point symmetric dedicated data connection over a fibre pair. Four types of leased line services are modelled, depending on the end points[5]. Figure 4 shows the high-level physical architecture of the Ethernet Leased Lines in scope for the model.

- EAD LA: a single premises connected to its local exchange
- EAD (no mainlink): two premises connected point-to-point, served by the same Exchange
- EAD (with mainlink): two premises connected point-to-point, served by different Exchanges
- EAD Backhaul (with mainlink): two Exchanges connected with a point-to-point fibre circuit

Figure 4.   *Ethernet Access Leased Lines High-Level Physical Architecture*
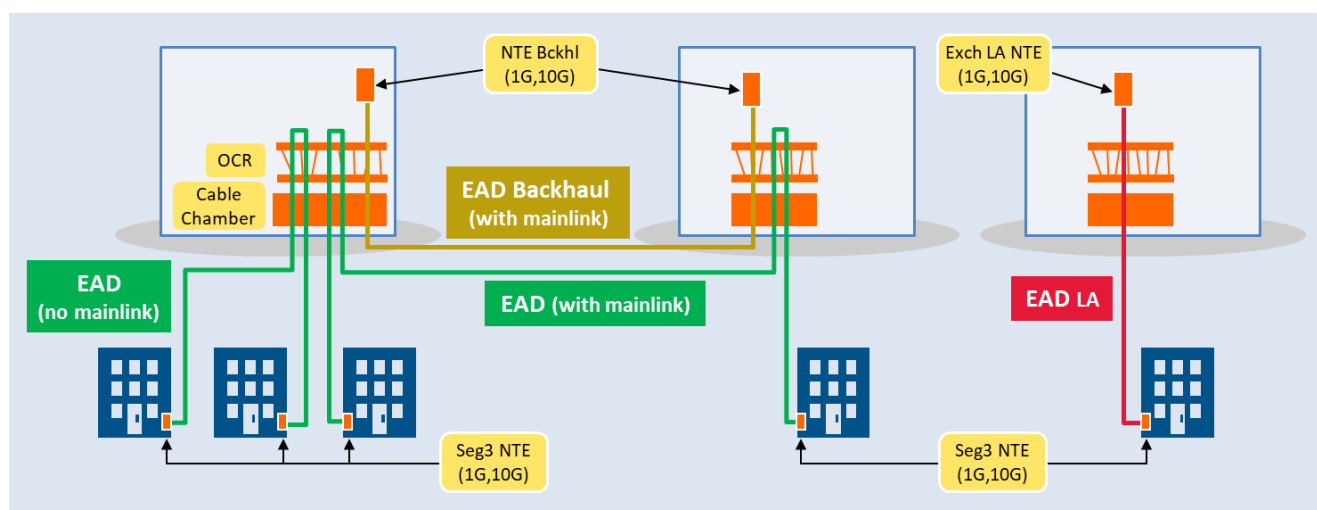
Source: Cartesian

4.10   With regards to data capacity, the model includes EAD and EAD LA volumes for 100Mbps, 1Gbps and 10Gbps, and EAD Backhaul volumes for 1Gbps and 10Gbps.

Network Elements

4.11   Fibre cable is modelled using the same three segments as with FTTP. We consider this to be reasonable as we expect an operator to install fibre cable for business services in the same physical infrastructure routes where the FTTP cables are installed. Figure 5 below shows the list of Network Elements for Ethernet Leased Lines.

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[5] We understand that there might be other types of leased line services, but these four were deemed representative of the vast majority of leased lines in the UK.

Figure 5. *Ethernet Leased Line List of Network Elements*

Element	Description
Shared components at the Exchange (CCJ, OCR, Tie Cables, Accommodation)	A number of network components at the Exchange are shared amongst all services, e.g. all cables are connected to the Cable Chamber Joint and are connected via tie cables to the OCR. Additionally, the racks occupied by the Leased Lines network components also contribute to the Exchange Accommodation costs, as explained in Figure 3
Exch Eth LA NTE (1G, 10G)	Network Termination Equipment at the Exchange, which terminates the EAD LA circuit that has a business premises at the other end of the circuit. The 1Gbps variant is used for both 100Mbps and 1Gbps circuits, whereas the 10Gbps variant is used exclusively for EAD LA 10Gbps.
Exch Eth Bckhl NTE (1G, 10G)	Network Termination Equipment at each end of an EAD Backhaul circuit (which connects two Exchanges) with two speed variants, 1Gbps and 10Gbps.
BCKH Business Serv Mainlink Fibre	This component models the amount of fibre required for dedicated business services requiring Exchange-to-Exchange connections. This network component is shared by all relevant business services, i.e. EAD, EAD Backhaul, Optical Services and Dark Fibre. This network component unit cost (per m) represents the proportional cost of 2 fibres of a 276f fibre cable, i.e. Cost_276f *(2/276). The module includes a parameter to represent the average length of an Inter-Exchange mainlink connection. Every fibre has an associated *fibre testing* cost, which is captured in a separate cost component
Segment 1,2,3 Business Serv Fibre (OH and UG)	This component models the amount of fibre cable required for dedicated business services (i.e. Ethernet leased lines, optical services, dark fibre) at each segment of the access network (Segments 1, 2, 3). We model an individual cable of 4 fibres for each new business service provision. The length of this fibre cable is provided by the Geospatial Analysis (average fibre length per business for each postcode sector, at each network segment; we use the coverage deployment matrix to calculate the weighted average length per business for each deployment year). This approach might over-dimension the costs of business fibre cables, as an efficient operator will likely use larger cables serving multiple business premises in a cluster. .
Segment 3 Eth NTE (1G, 10G)	The Network Termination Equipment, located in the customer premises, terminates the optical connection and presents a service interface to the customer. As per Figure 4 this component is required for EAD provisions (one NTE at each of the two end-premises) and EAD LA provisions (one NTE at the customer side).
Segment 3 BusServ Connection Civils	This component models the civils work required to install the equipment at the business premises. It is required for all business services provisions with customer end-points (EAD, EAD LA, Optical Access Services and dark fibre Access services). We assume the unit cost is the same for all business services.

Source: Cartesian

Optical Services

Technology Overview

4.12 Optical Services refers to dedicated optical point-to-point fibre links, using wavelength division multiplexing (WDM) technology[6]. We model three types of Optical services, differentiated by their end points. For simplicity, we have not modelled the LA variant for optical services as this would add further complexity, without having a significant impact on modelled costs due to their low volumes in the real world. Figure 6 below shows the high-level physical architecture of the Optical Services in scope for the model.

- Optical Service - Access (no mainlink): two premises connected point-to-point, served by the same Exchange
- Optical Service - Access (with mainlink): two premises connected point-to-point, served by different Exchanges[7]
- Optical Service - Backhaul (with mainlink): two Exchanges connected with a point-to-point fibre circuit

Figure 6. *Optical Services High-Level Physical Architecture*
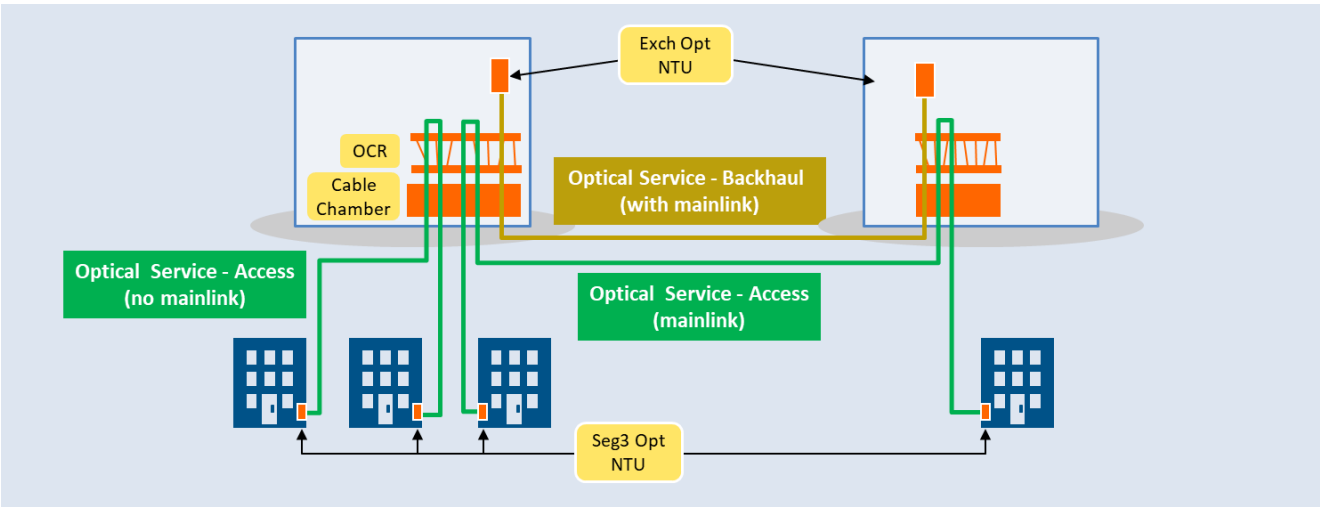
Source: Cartesian

Network Elements

4.13 Fibre cable is modelled in three segments, similar to Ethernet leased lines. The table below shows the list of Network Elements for Optical Services.

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[6] Optical Spectrum Access (OSA) In Openreach's terms
[7] We note that mainlink volumes are forecasted independent of whether a circuit is EAD, optical or dark fibre, thus the model implicitly forecasts optical access circuits where the two premises are at the same exchange, i.e. no mainlink.

Figure 7. ***Optical Services List of Network Elements***

Element	Description
Shared components at the Exchange (CCJ, OCR, Tie Cables, Accommodation)	A number of network components at the Exchange are shared amongst all services, e.g. all cables are connected to the Cable Chamber Joint, and are connected via tie cables to the OCR. Additionally, the racks occupied by the Optical Service active components also contribute to the Exchange Accommodation costs.
Exch Opt NTU (1G, 10G)	Equipment located at the Exchange, terminating each end-point of the Optical Service – Backhaul circuit between two Exchanges. The NTU costs include the cost of the chassis and the wavelength card.
BCKH Business Serv Mainlink Fibre	This component models the amount of fibre required for dedicated business services requiring Exchange-to-Exchange connections. This component is shared with Ethernet Leased Lines and Dark Fibre, as explained in Figure 3.
Segment 1,2,3 Business Serv Fibre (OH and UG)	This component models the amount of fibre cable required for dedicated business services (i.e. Ethernet leased lines, optical services, dark fibre) at each segment of the access network (Segments 1, 2, 3). The same component is used by Ethernet Leased Lines and more detail is provided in Figure 3.
Segment 3 Opt NTU	Equipment located at the customer premises, terminating each end-point of the Optical Service – Access circuit between two business premises. The NTU costs include the cost of the chassis and the wavelength card.
Segment 3 BusServ Connection Civils	This component models the civils work required to install the equipment at the business premises. The same component is used by Ethernet Leased Lines and more detail is provided in Figure 3.

Source: Cartesian

Dark Fibre

Technology Overview

4.14 Dark Fibre is modelled as a point-to-point, unlit fibre pair connection between two end-points. Three types of dark fibre services are modelled, differentiated by the connection points. For simplicity, we do not model the LA variants for this service as we think it sufficient to approximate the cost of these circuits as half of the modelled dark fibre access circuit.[8] Figure 8 below shows the high-level physical architecture of the dark fibre services in scope for the model.

- Dark Fibre - Access (no mainlink): two premises connected point-to-point, served by the same Exchange
- Dark Fibre - Access (with mainlink): two premises connected point-to-point, served by different Exchanges[9]
- Dark Fibre - Backhaul (with mainlink): two Exchanges connected with a point-to-point fibre circuit

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[8] We note that this might understate the number of patch panels at the exchange as LA variants would require a patch panel at the exchange whilst the access service illustrated in Figure 8 would not. However, we believe that this simplification does not have material consequences, as the Exchange Patch Panel costs are very low in comparison to other cost items of the service (e.g. fibre cables)

[9] We note that mainlink volumes are forecasted independent of whether a circuit is EAD, optical or dark fibre, thus the model does implicitly forecast dark fibre access circuits where the two premises are at the same exchange, i.e. no mainlink.

4.15 A CP procuring dark fibre will install network equipment at each end of the fibre pair since the dark fibre service is not supplied with active equipment.

Figure 8. *Dark Fibre High-Level Physical Architecture*
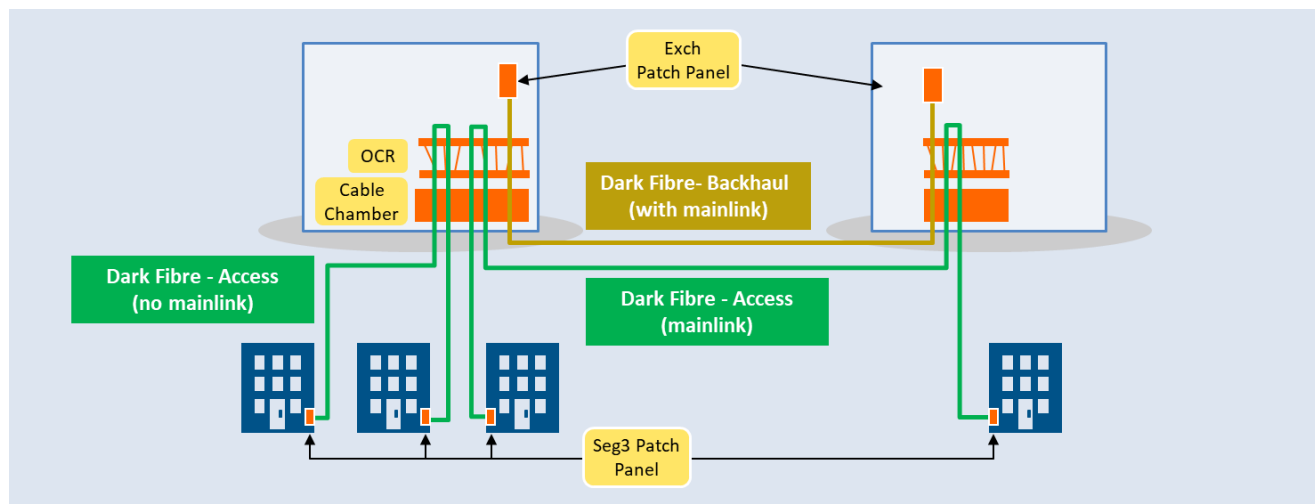
Source: Cartesian

Network Elements

4.16 We model the fibre cable in three segments, similar to the business dedicated services explained above. Figure 9 below shows the list of Network Elements for Dark Fibre.

Figure 9. *Dark Fibre List of Network Elements*

Element	Description
Shared components at the Exchange (CCJ, OCR, Tie Cables)	A number of network components at the Exchange are shared amongst all services, e.g. all cables are connected to the Cable Chamber Joint, and are connected via tie cables to the OCR
DF Patch Panel (Exch and Segment 3)	The DF Patch Panel represents the demarcation point of the dark fibre service, at the exchange (Exch DF Patch Panel) at the customer premises (Seg3 DF Patch Panel)
BCKH Business Serv Mainlink Fibre	This component models the amount of fibre required for dedicated business services requiring Exchange-to-Exchange connections. This component is shared with Ethernet Leased Lines and Optical services, as explained in Figure 3
Segment 1,2,3 Business Serv Fibre (OH and UG)	This component models the amount of fibre cable required for dedicated business services (i.e. Ethernet leased lines, optical services, dark fibre) at each segment of the access network (Segments 1, 2, 3). The same component is used by Ethernet Leased Lines and more detail is provided in Figure 4
Segment 3 BusServ Connection Civils	This component models the civils work required to install the equipment at the business premises. The same component is used by Ethernet Leased Lines and more detail is provided in Figure 4

Source: Cartesian

Duct and Pole Access (DPA)

Technology Overview

4.17 The DPA service provides space in underground ducts and/or on overhead poles for the installation of fibre cables

4.18 A 'DPA subscriber' requires sufficient cross-sectional physical space, on a pole or in a duct, for the installation of fibre using the pole or duct. In the Volumes Module DPA volumes are disaggregated by service (FTTP, Leased Line) and by network segment, as the various services may have different implications on physical space requirements:

- DPA FTTP at Segment 1: the cross-section of one fibre at Segment 1 serves N 'DPA Subs', where N is the split ratio (see 4.4 - 4.5 for more details on the split ratios used)
- DPA FTTP at Segment 2 and 3: one subscriber at these segments would take the cross-sectional space of one fibre
- DPA Leased Lines (all segments): each subscriber would require the cross-sectional space of a cable of 4f (we are using this cable to model fibre length for business services, as explained for the element 'Segment 1,2,3 Business Serv Fibre' in Figure 4)

Network Elements

4.19 The only network elements used by DPA are the passive infrastructure elements (e.g. ducts, poles, microtrench and sub-ducts) which are shared by all services. The approach to dimension these elements is covered in the Infrastructure Module (Section 7).

5   Model Structure

High-Level Description of Model Structure

5.1 Cartesian has developed four separate, inter-related modules:

- The Geospatial analysis processes the location of all the premises in the UK, road topologies and relevant network assets to calculate a set of output parameters which are consumed by the Network Model to dimension the target network appropriately;
- The Infrastructure Module takes the outputs from the Geospatial analysis, the service demand and the premises coverage forecast (both provided by Ofcom), to dimension the underground physical infrastructure, i.e. new duct, existing duct, in Segments 1 and 2;
- The Network module takes the outputs from the Geospatial analysis, the service demand, the premises coverage forecast and Infrastructure Module to dimension the network;
- The Cost module calculates the capital expenditure required to build the dimensioned network.

5.2 The outputs from the Cost module are used by the Cost Recovery module, developed by Ofcom, to calculate how costs are recovered over time and across services. Operating costs are also calculated in Ofcom's Cost Recovery module.

5.3 The Infrastructure, Network and Cost modules were developed in Microsoft Excel (one file for the Infrastructure module, and another file combining the Network and Cost modules). The Geospatial

analysis was conducted using PostgreSQL, R and Python. The output parameters of this analysis are included in an input interface sheet contained in the Network module. Figure 10 below shows the relationship between the modules.

Figure 10.   *Overall Full-Fibre Model Architecture*
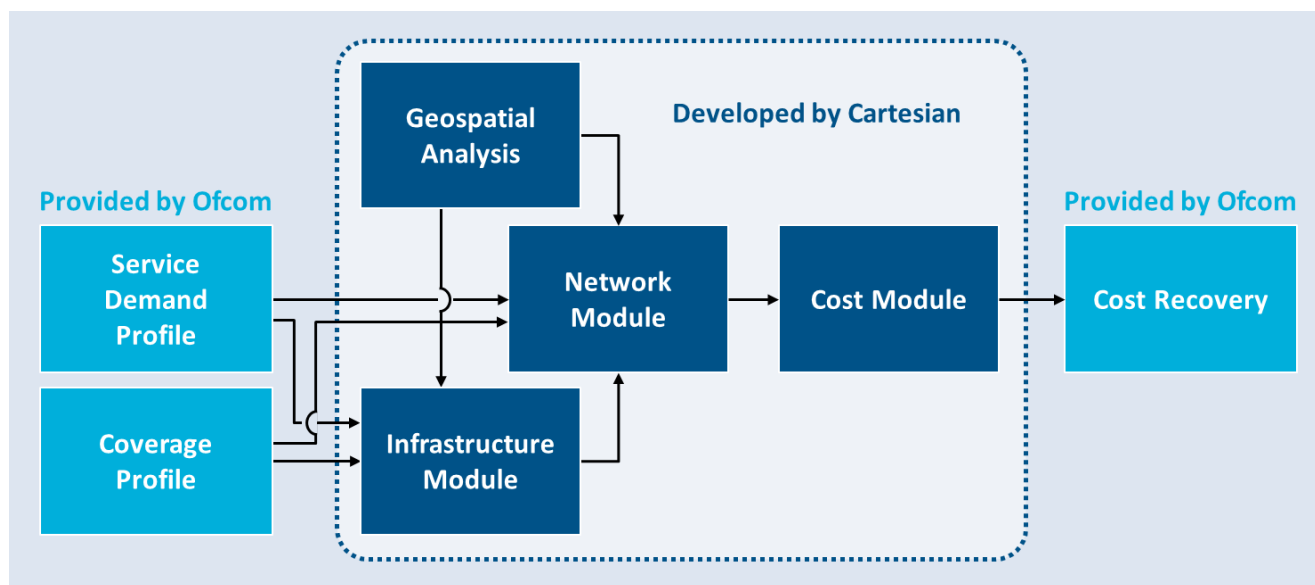
Source: Cartesian

Coverage Deployment

5.4   The annual forecast of covered premises by Geographic Area from the Volumes module forms an input to the network cost model (shown as 'Coverage Profile' in the diagram above). Using these forecasts, the model then determines which postcode sectors are deployed each year in each Geographic Area, using a ranking of postcode sectors by cost (with the lowest cost postcode sectors in a given Geographic Area being deployed first).

5.5   The rationale for this approach is that an operator is likely to start deploying its network in the most cost-effective regions within a Geographic Area. For the ranking, Cartesian uses a proxy to determine costs as the geospatial parameters do not include costs. The average length of physical passive infrastructure per premises at Segments 1, 2 and 3 is used as the cost proxy and is considered reasonable given that civil costs typically represent most of the deployment costs. The output of this analysis is a deployment matrix of 'postcode sectors' (rows) and deployment years (columns), showing '1' and '0' depending on whether the postcode is to be deployed.

Service Demand and Allocation to Postcode Sectors

5.6   Ofcom's Volumes module contains the annual subscriber volume forecasts for each of the services in scope. The output of the Volumes module is used as an input sheet to the Network model. The service volumes are broken down by service, Geographic Area (i.e. 1, 2 and 3), and Access vs Backhaul.

5.7   The service volumes are allocated into individual postcode sectors using a simple allocation method based on the shares of residential and large business premises in each postcode sector, and consistent with the coverage rollout profile described in paragraphs 5.4 – 5.5.

Consistency between Coverage and Demand inputs

5.8   The mapping of postcode sectors to Geographic Area (i.e. 1, 2, 3), which is used to set the coverage deployment plan, should be consistent with the coverage and service demand input data. To this end, we have built a simple error check tool in the network cost model (in the Link_Service Volume worksheet) to highlight potential inconsistencies between these input data sources, including:

- If the number of premises covered by Geographic Area after mapping to postcode sectors is lower than the total number of premises to be covered in each Geographic Area. The figures are calculated for the last year of the model.
- If the number of FTTP subscribers (FTTP + DPA FTTP) in each Geographic Area is larger than the number of premises covered at these Geographic Areas.

6   Geospatial Model Approach and Assumptions

<u>Technology Overlay Modelling</u>

6.1   We assume that all services use the same passive infrastructure routes (ducts and poles). This is an approach which operators are expected to use in a hybrid residential/business network deployment. As a result of all services using the same passive infrastructure, there is only one set of geospatial parameters.

6.2   Given that aggregated service volumes are used to dimension the network, the cost model uses average geospatial parameters within postcode sectors (the geographic unit).

6.3   Taking the above considerations into account, we use the following approach to dimension the network services:

Figure 11.   *Approach to Dimension Network Services*

Service	Approach
FTTP	• We model FTTP as a service covering all premises within a postcode sector. We use the Geospatial Analysis to determine the passive infrastructure and fibre requirements for the various network segments of each postcode sector
Ethernet Leased Lines **Optical Services** **Dark Fibre**	• We use the locations of large businesses to estimate the average route lengths to these locations for each network segment[10]. The exact details of how these average lengths are calculated for each network segment are explained in paragraphs 6.38 - 6.40. • We then calculate the incremental network elements at each postcode sector required to deliver the forecasted leased line and dark fibre volumes (i.e. on top of the network elements required to deliver FTTP).
DPA	• We calculate the amount of passive infrastructure required to serve the DPA-based subscribers estimated in the Volumes module; we also calculate the amount of passive infrastructure required by the other services. • From this, we calculate the total amount of passive infrastructure required to deliver all services. See Section 7 (Infrastructure Module) for more details on how the passive infrastructure is dimensioned

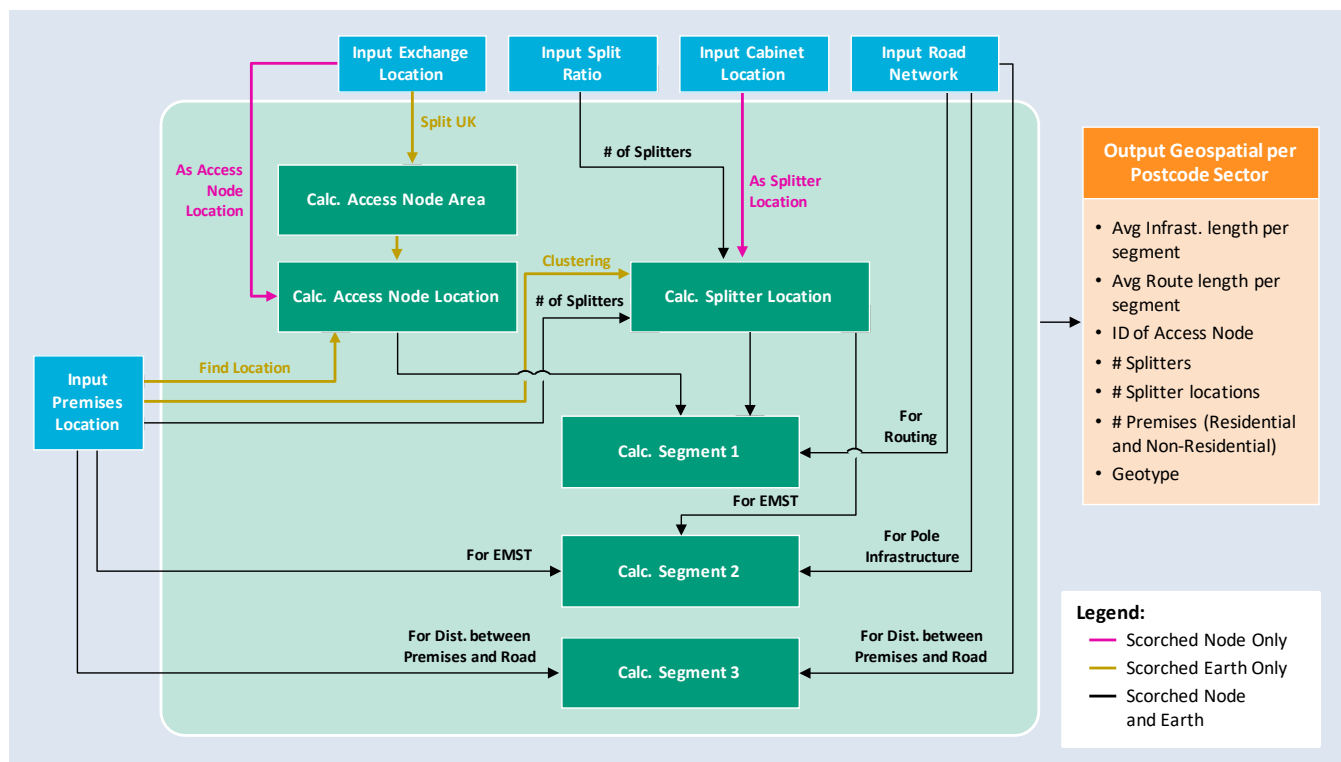Source: Cartesian

<u>High-Level Geospatial Approach</u>

6.4   As described in paragraphs 3.9 - 3.10, we have developed two Geospatial Models: 1) a Scorched Node model, which assumes that an efficient operator re-uses the existing location of Cabinets and Exchanges from Openreach; 2) a Scorched Earth model, where the efficient operator does not re-use these existing Openreach sites.

6.5   The Geospatial Model calculates the number of splitters, and lengths of infrastructure (overhead and underground) and fibre cable (overhead and underground) required for 100% coverage of premises.

---

[10] For those businesses for which we have the postcode unit, but not the actual coordinates, we used the location of the postcode unit centroid as a proxy for the actual business location.

The Network Cost Model then apportions the network route between ducts and poles using the amount of underground and overhead infrastructure at each network segment (input parameter in the cost model) to determine the infrastructure and network elements in each postcode sector.

6.6   The Geospatial Model uses several data input files to calculate a set of output parameters, which are consumed by the Network Cost Model to dimension the network.[11]

6.7   The figure below illustrates the high-level architecture of the FTTP Geospatial Model.

Figure 12.   *High-Level Architecture of the Geospatial Model*

Source: Cartesian

6.8   The model calculates the physical passive infrastructure and fibre cable requirements for the standard 1:32 splitters for all postcode sectors, and calculates the same parameters for the 1:16 splitters for postcode sectors within Area 3[12]. Both sets of outputs (i.e. for 1:16 and 1:32 splitters) are used as inputs by the Network Cost Model, where they are selected as required.

---

[11] An example to illustrate this point: The Geospatial Model calculates the total underground infrastructure length if all premises were connected with underground ducts, and it also calculates the overhead infrastructure length if all premises were connected with overhead poles. The network model then has a set of input parameters to determine the split overhead/underground infrastructure in each network segment, and applies this share to the infrastructure length figures from the Geospatial Model

[12] The rationale is explained in detail in paragraph 4.5

Access Node and Splitter Location

6.9   In scorched node the Access Nodes are located at Openreach fibre exchanges and the splitters are located at Openreach cabinet sites. In scorched earth the locations of access nodes and splitters are determined algorithmically, using the location of customer premises.

6.10   We used the road network from OpenStreetMap for routing the physical passive infrastructure and fibre requirements along the roads (from Access Node to Splitter Location). Access nodes, exchanges, and splitter locations were assigned to their closest road to establish the start and end point of the route.

Scorched Node

6.11   Openreach fibre exchange locations were used as the access nodes, and the location of Openreach's copper cabinets were used as the splitter locations. Although we use cabinet locations, we are not assuming that the splitters will be physically housed in the cabinet.

6.12   Where a cabinet is served from a copper exchange, the fibre is routed to the serving fibre exchange via the copper exchange, as we believe that operators in the real world would likely follow this approach.

Scorched Earth

6.13   The Scorched Earth model determines the location of the access node based on the distribution of customer premises. We used Openreach's fibre exchanges as a starting point on the basis that an entrant operator would likely follow similar general coverage patterns as Openreach's fibre exchanges (more access nodes in dense areas and fewer in sparse areas).

6.14   Using the location of Openreach's fibre exchanges we segment the country into serving areas, assigning each premises to their closest fibre exchange. We then recalculate the location of the access node to be the centroid of the serving premises (see Figure 13). Premises within the serving area of an access node are clustered separately using K-Means[13].

---

[13] K-Means is an algorithm that partitions N observations into K clusters in which each observation belongs to the nearest cluster. See https://en.wikipedia.org/wiki/K-means_clustering for more details

Figure 13. *Example of Access Node Location Moving in Scorched Earth*
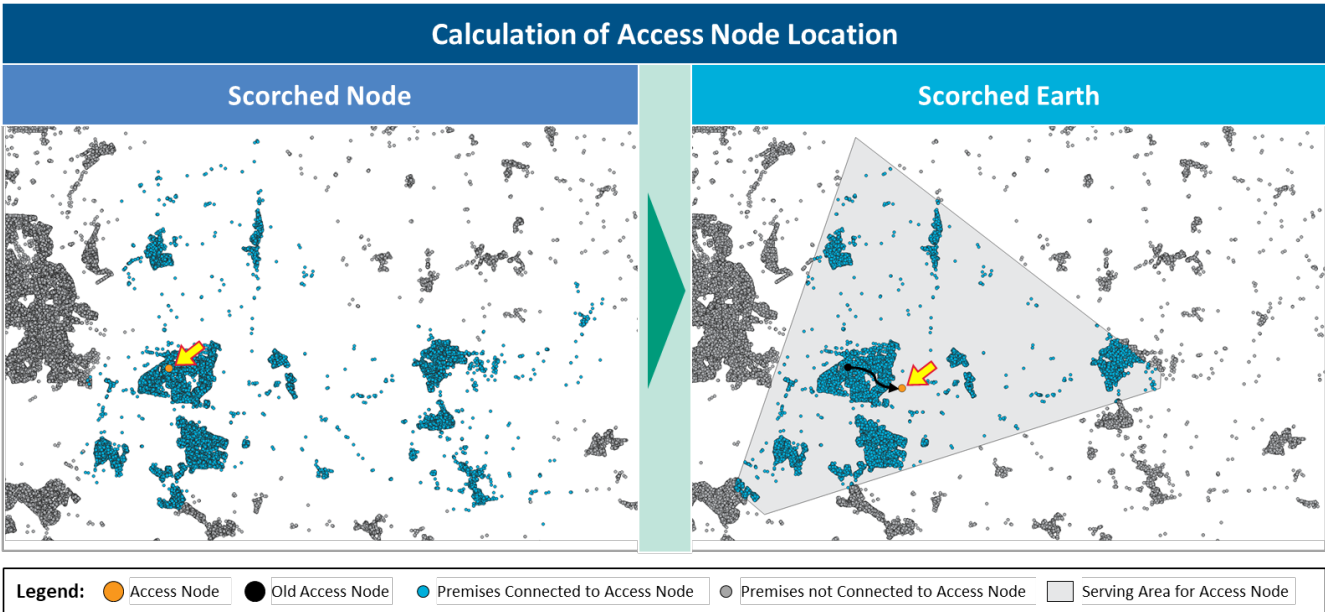
Source: Cartesian

Segment 1: Access Node to Splitter

6.15 Routing from the access node to the splitter location follows the road network. In the case of scorched node routing is via Openreach's existing copper exchanges where appropriate. Physical passive infrastructure (i.e. ducts and poles) can be shared between multiple Segment 1 routes (i.e. multiple routes from the access node to different splitters locations can share the same ducts and/or poles). The route length is used to estimate the physical passive infrastructure and fibre requirements. See Figure 14 for an example of the Segment 1 routing.

Figure 14.　*Example of Segment 1 Routing*
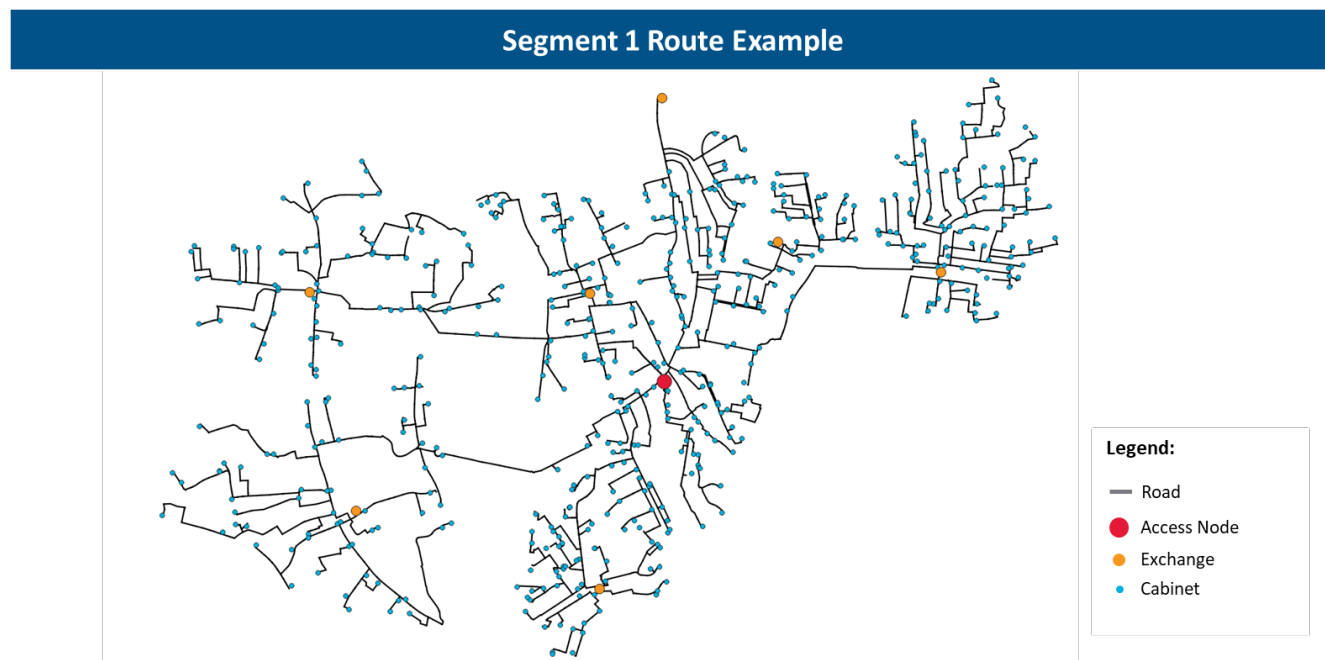
Source: Cartesian

6.16　For Segment 1, duct and pole infrastructure are treated equally, as the road distance from the access node to splitter location is the same regardless of it being aerial or underground.[14]

6.17　To find the shortest path via roads between access nodes and splitters we used Dijkstra's shortest path algorithm[15]. For routes that could not be found (e.g. access node and splitter location separated by sea) we approximated the distance as 1.4 multiplied by the crow-flies distance.[16]

6.18　We determine the effective length of fibre cable needed to connect a splitter by multiplying the route length by the number of splitters at that site, dividing by 36 (number of fibres in a cable), and rounding the value up to the nearest integer. It is assumed that only one cable modularity (36 fibres) is used.

6.19　The physical passive infrastructure (i.e. ducts and poles), if shared by multiple splitter locations, is apportioned to each splitter location based on the number of splitters at each of those locations. This means that the sum of the Segment 1 length assigned to all cabinets equals the total unique length needed) and means that cabinets with more splitters will receive a larger 'share' of the infrastructure length than cabinets with fewer.[17] See Figure 15 for an example calculation.

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[14] Duct and pole infrastructure is treated differently in the Network Cost Model, but in segment 1 in the geospatial model they are calculated the same but pole lengths are increased by the height of the poles.
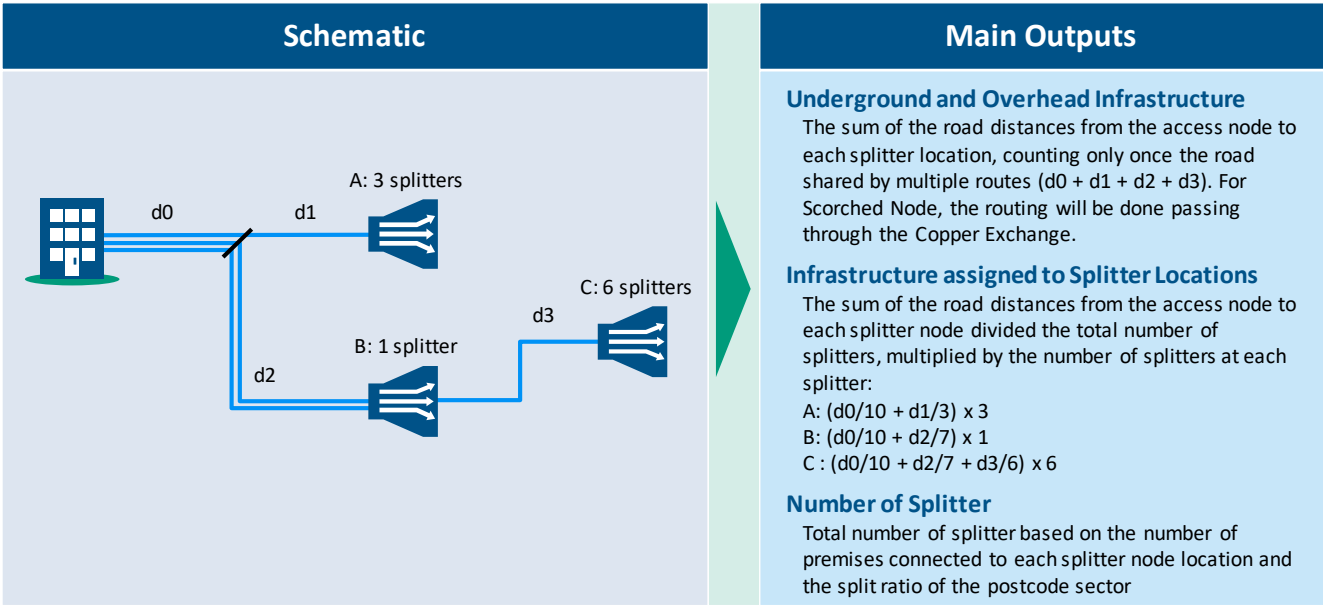
[15] See https://en.wikipedia.org/wiki/Dijkstra%27s_algorithm for the algorithm. We have considered other approaches (A*, etc.) but Dijkstra's is faster for one-to-many applications (e.g. routing from one access node to many exchanges).

[16] Based on Cartesian experience with similar situations.

[17] This only applies to roads that are used in the routes of multiple splitter locations, roads only used by one splitter location are assigned entirely to that splitter location.

Figure 15. ***Example of Segment 1 Estimation Using Road Distance***

Schematic	Main Outputs
	Underground and Overhead Infrastructure The sum of the road distances from the access node to each splitter location, counting only once the road shared by multiple routes (d0 + d1 + d2 + d3). For Scorched Node, the routing will be done passing through the Copper Exchange. **Infrastructure assigned to Splitter Locations** The sum of the road distances from the access node to each splitter node divided the total number of splitters, multiplied by the number of splitters at each splitter: A: (d0/10 + d1/3) x 3 B: (d0/10 + d2/7) x 1 C : (d0/10 + d2/7 + d3/6) x 6 **Number of Splitter** Total number of splitter based on the number of premises connected to each splitter node location and the split ratio of the postcode sector

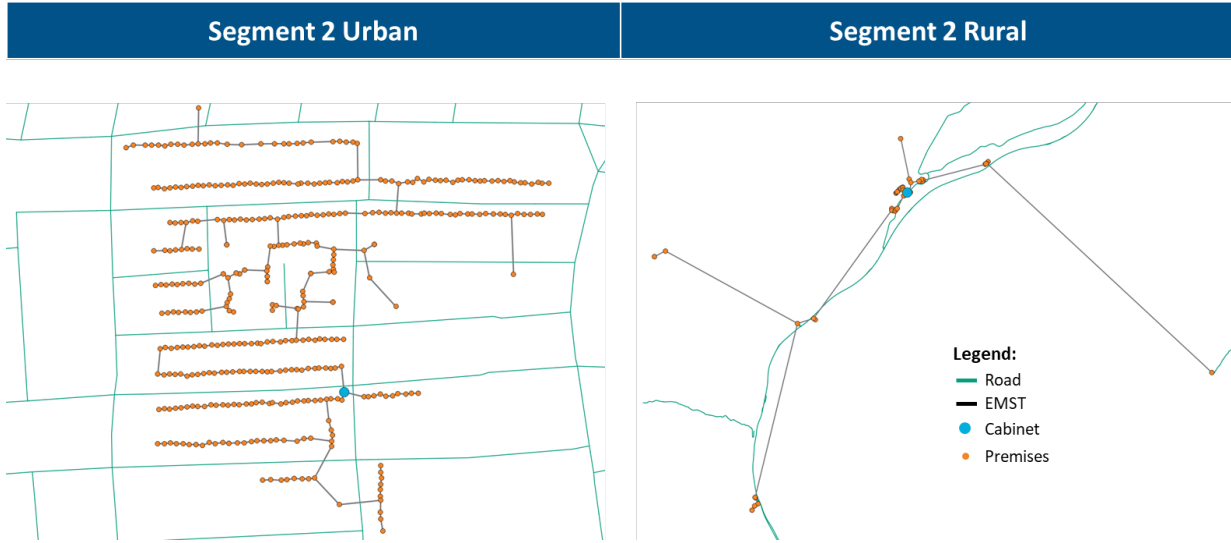Source: Cartesian

Segment 2: Splitter to Distribution Point

6.20 For this segment the methodologies for duct and pole distance estimation differ – for underground access the network must run past premises on both sides of the street but for overhead the network only needs to go down one side.

Underground Infrastructure

6.21 The physical infrastructure required for 100% underground coverage is approximated with a Euclidian Minimum Spanning Tree (EMST)[18]. As can be seen in Figure 16, this provides a good approximation for the network infrastructure needed in dense urban areas and is also reasonably accurate for rural areas.

---

[18] EMST interconnects all premises with the Splitter Location using lines such that the total length of all lines is minimised. See https://en.wikipedia.org/wiki/Minimum_spanning_tree and https://en.wikipedia.org/wiki/Euclidean_minimum_spanning_tree.

Figure 16.   ***Example of Urban and Rural EMST for Segment 2***

Source: Cartesian

6.22   We use the lines produced by the EMST to interconnect the premises with the splitter location to determine the fibre requirement to connect each premises to the splitter location. Using the EMST, we calculated the total distance from the splitter location to each premises. This total fibre distance is divided by 36 (to approximate the fibre length into metres of fibre cables).

6.23   To avoid double counting physical passive infrastructure between Segment 1 and 2, the model removes segments that have already been traversed in Segment 1.

Aerial Infrastructure

6.24   The physical passive infrastructure required for 100% overhead coverage is approximated using the street lengths. Each premises is given a *share of road length* by dividing the length of its assigned road (the nearest road) by the number of premises assigned to that road. The aerial infrastructure is the sum of the share of road length for all premises belonging to a splitter location. This methodology ensures we do not count the same street multiple times.

6.25   To determine the aerial fibre requirements, we assume that the ratio of aerial to underground *fibre* for each splitter location is equal to the ratio of aerial to underground *infrastructure* for that splitter location. This means that the overhead fibre will be equal to the ratio of underground fibre to underground infrastructure times the overhead infrastructure.[19]

6.26   To avoid double counting infrastructure between Segment 1 and 2, the model removes segments that have already been traversed in Segment 1.

---

[19] The ratios are constant, so: $\left(\frac{d_{fibre}}{d_{infra}}\right)_{aerial} = \left(\frac{d_{fibre}}{d_{infra}}\right)_{underground}$. Therefore we can calculate the aerial fibre length like so:

$$d_{fibre,aerial} = d_{infra,aerial} \cdot \left(\frac{d_{fibre}}{d_{infra}}\right)_{underground}$$

6.27   In some cases, almost the entirety of the Segment 2 has already been covered by Segment 1. The distance reported by the model here can sometimes be zero or slightly negative – for these cases we set the length of Segment 2 to zero. This occurs in only 0.3% of splitter locations in scorched node and 0.1% of splitter locations in scorched earth.

6.28   There is no concern regarding double counting of fibre cables since we assume that fibre cables are not shared between Segment 1 and 2 or within Segment 1 (access node to splitter locations).

Segment 3: Distribution Point to Premises

6.29   The methodologies applied in Segment 3 for duct and pole are different. We assume infrastructure lengths and fibre lengths here are equal, and that each premises is connected individually to the network. We have not factored in Multi-Dwelling Units (MDUs) with one entry point serving multiple premises. This is because the data used did not have the entry point of each premises, hence we assumed that each premises is connected independently.

Underground Infrastructure

6.30   For Segment 3 underground infrastructure and fibre requirements, the model calculates the distance from the premises to the nearest road and assigns that to the premises (see Figure 17).

Aerial Infrastructure

6.31   For poles we estimate the average distance to a pole assuming premises are uniformly distributed between poles[20]. This is calculated irrespective of road shape, i.e. we assume the road is straight between poles. Taking the distance between premises and the road; and average distance between poles, we used trigonometric functions to estimate the distance between the poles and premises (see Figure 17, bottom right diagram).

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[20] We used 50 metres as the average distance between poles.

Figure 17. ***Example of Segment 3 Estimation***
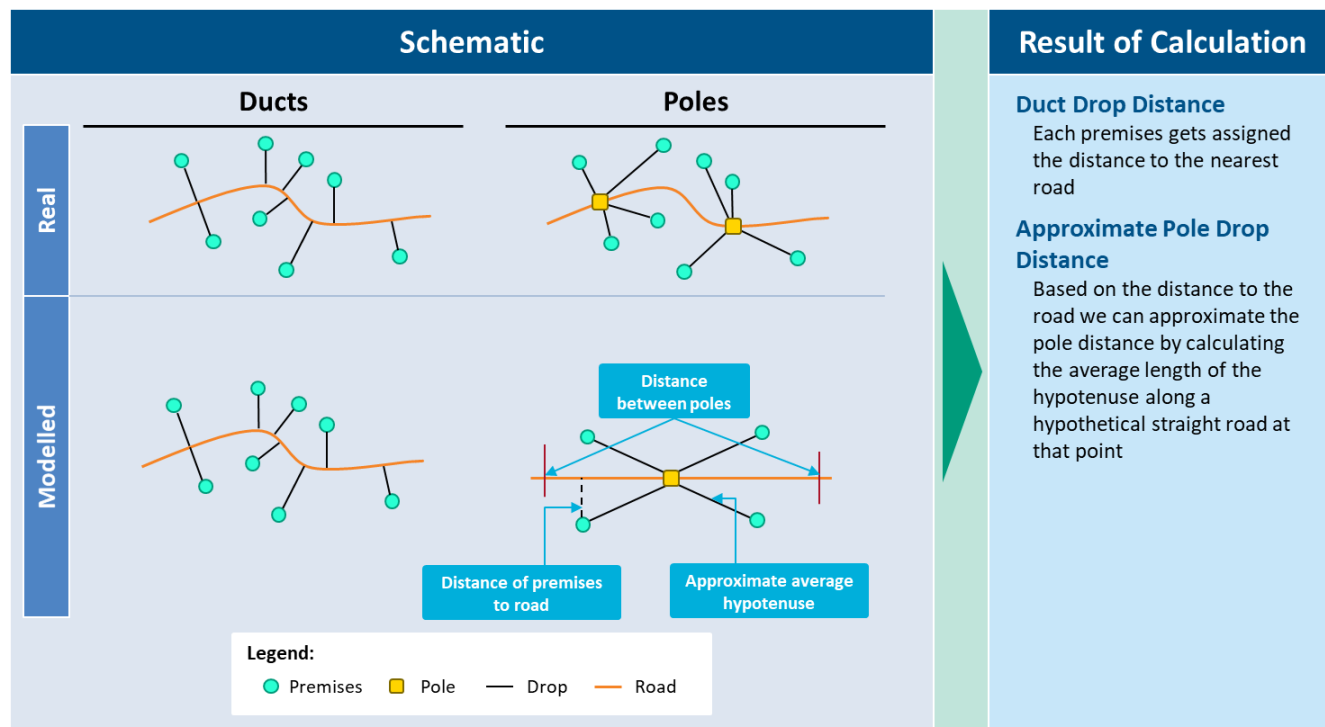
Source: Cartesian

Split Ratio

6.32 As described in paragraph 4.4 - 4.5, the model uses 1:32 splitters as standard for all the UK, and 1:16 for the premises in Geographic Area 3 with longer fibre spans to the exchange. The entire country is calculated using 1:32 splitters for both scorched earth and scorched node. This analysis is then repeated for premises in Geographic Area 3, using 1:16 splitters. This allows the Network Cost Model to choose between 1:32 and 1:16 splitters in postcode sectors within Geographic Area 3 without having to re-run the Geospatial Model.

6.33 For Scorched Node, using 1:16 splitters changes the number of splitters required at each location and the number of fibres needed in Segment 1. Since the locations of Access Node, Exchange and Splitter are unchanged, Segment 1 physical passive infrastructure is the same, and Segment 2 and 3 physical passive infrastructure and fibre requirements are the same.

6.34 For Scorched Earth however, using 1:16 splitters changes how the premises are clustered, so the analysis is re-run from start to finish for Geographic Area 3.

6.35 The Geospatial output contains both 1:32 splitter results and 1:16 splitter results for postcode sectors in Geographic Area 3 as both are needed in the Network Cost Model.

Large Businesses and Mobile Sites

6.36   Business and mobile sites are treated completely separately to residential premises and are kept separate throughout the Geospatial Model. Business premises and mobile sites are treated identically in the Geospatial Model and are collectively referred to as business premises in the following text.

6.37   Of the 149k businesses sites, 37% had an exact location. For the remainder, we used the location of postcode unit centroid as an approximation of the business premises location.

6.38   The raw information used did not contain the Exchange or Cabinet to which each business is connected to, so we assumed they are connected to the Exchange serving the residential premises in the same postcode unit. The model calculates Segment 1 length by averaging the Segment 1 length to those splitter locations serving premises located in the same postcode unit as the business sites.

6.39   Segment 2 distances are averaged distances between the business site and splitter locations that serve premises in the postcode unit of the business, weighted by the number of premises the splitter location serves in the postcode unit (so that a splitter location that serves many premises will have a greater weight in the average and a splitter location serving zero premises in that postcode unit will have no weight).

6.40   For Segment 3 we take the same approach as with residential, finding the distance from the business premises to the nearest road. Even though the exact position of the business is not always known, this provides a good approximation for Segment 3.

Outputs to Network Cost Model

6.41   The outputs to the Geospatial Model are summarised at a postcode sector level. Figure 18 describes the Geospatial parameters that are used as inputs by the Network Cost Model. There are two sets of parameters, for Scorched Node and for Scorched Earth (the parameters have the same name, and they are included in the worksheets 'Input Geo SN' and 'Input Geo SE' of the Network Cost model, respectively). All parameters specific to a splitter ratio (1:32 or 1:16) will appear twice, and will have _32 and_16 appended to the parameter name (e.g. *example_parameter_32*).

Figure 18.   *Summary of Geospatial Model Outputs Used by the Network Model*

Variable	Description
rank_ug_infra_length_total	• Ranking of postcode sectors (in ascending order) by the total length of underground physical passive infrastructure (ug_infra_length_total_32). The ranking can be different for Scorched Node and Scorched Earth (as the infrastructure distances may be different)
postcode_sector	• Postcode sectors of all premises included in the analysis (9,513 postcode sectors)
infra_geotype_id	• Geotype of the Exchange that serves the majority of premises in the postcode sector
geographic_area	• Geographic area of the postcode sector (input parameter from Ofcom)

Cartesian: Fixed Telecom Access – Full Fibre Modelling

Variable	Description
premises	• Number of premises included in the analysis belonging to the postcode sector (based on Ordnance Survey)
biz_premises	• Number of large businesses or mobile sites in the postcode sector
access_node_id	• Identifier of the Access Node that serves the majority of premises in the postcode sector
ug_infra_length_seg1 and oh_infra_length_seg1	• Total length, in metres, of the physical passive infrastructure from the Access Nodes to the Splitter Locations in a postcode sector (we use the same values for overhead and underground infrastructure at this segment) • Refer to paragraphs 6.15 - 6.19 for details on the calculations
ug_fibre_length_seg1 and oh_fibre_length_seg1	• Total length of FTTP fibre cables (36f), from the Access Nodes to the Splitters in a postcode sector. Details on the calculations can be found on paragraph 6.18 • To calculate the length of the overhead fibre, we add 4x the pole height to the length of the underground fibre (see Figure 17 for an illustration of the route of an overhead fibre cable; we use a pole height of 9 metres)
ug_cable_cross_sect_fttp_avg_seg1	• Average number of cross-sectional FTTP fibre cables (36f) required to serve FTTP in a postcode sector in Segment 1 • This is calculated by dividing the ug_fibre_length_seg1 by ug_infra_length_seg1 before de-duplication, for each postcode sector. We then divide the result by 36 and round it up to the nearest integer to obtain the number of 36f cables
ug_fibre_length_seg1_avg_biz_serv	• Average underground fibre cable length per business at Segment 1, in metres • The method to calculate this parameter is explained in paragraph 6.38
oh_fibre_length_seg1_avg_biz_serv	• Average overhead fibre cable length per business at Segment 1, in metres. It is calculated by adding 4x the pole height to the parameter above (ug_fibre_length_seg1_avg_biz_serv)
splitter_count	• Total number of splitters at each postcode sector. See paragraphs 6.32 - 6.35 for more details
splitter_biz_count	• Total number of splitters in those Splitter Locations of a postcode sector that serve premises located in the same postcode unit as business sites
ug_infra_length_seg2	• Total length, in metres, of the underground passive infrastructure at Segment 2 • Details of the calculations can be found in paragraphs 6.21 - 6.23
oh_infra_length_seg2	• Total length, in metres, of the overhead passive infrastructure at Segment 2 • Details of the approach to calculate this parameter can be found in paragraphs 6.24 - 6.27
ug_fibre_length_seg2	• Total length of underground FTTP fibre cables (36f), from the Splitter Nodes to the Distribution Points, in a postcode sector • See paragraph 6.22 for details on the calculations

Cartesian: Fixed Telecom Access – Full Fibre Modelling

Variable	Description
oh_fibre_length_seg2	• Total length of overhead FTTP fibre cables (36f), from the Splitter Nodes to the Distribution Points, in a postcode sector • See paragraph 6.25 for details on the calculations. We added 1x the pole height to the calculated figure to account for the fact that we assume that all splitter nodes are located underground
ug_cable_cross_sect_fttp_avg_seg2	• Average number of cross-sectional FTTP fibre cables (36f) required to serve FTTP in a postcode sector in Segment 2 • This is calculated by dividing the ug_fibre_length_seg2 by ug_infra_length_seg2 before de-duplication, for each postcode sector. We then divide the result by 36 to obtain the average number of 36f cables
ug_fibre_length_seg2_avg_biz_serv	• Average underground fibre cable length per business at Segment 2, in metres • The method to calculate this parameter is explained in paragraph 6.39
oh_fibre_length_seg2_avg_biz_serv	• Average overhead fibre cable length per business at Segment 1, in metres. It is calculated by adding 1x pole height to the parameter above (ug_fibre_length_seg2_avg_biz_serv)
ug_infra_length_seg3_avg, oh_infra_length_seg3_avg and, ug_fibre_length_seg3_avg	• Average length of premises to their nearest road, for each postcode sector (meters per premises). The model uses the same values for underground infrastructure and fibre, and overhead infrastructure • Details on the calculation can be found on paragraphs 6.29 - 6.30
oh_fibre_length_seg3	• Average length of the overhead fibre cable at segment 3, from the pole to the premises. See paragraph 6.31 and Figure 17 for more details
ug_fibre_length_seg3_avg_biz_serv and oh_fibre_length_seg3_avg_biz_serv	• Average length of business site to their nearest road, for each postcode sector. Details on the approach can be found in paragraph 6.40
ug_infra_length_total_32	• Average length of infrastructure at all network segments. • It is calculated using the following formula: (ug_infra_length_seg1 + ug_infra_length_seg2)/Premises + ug_infra_length_seg3_avg
max_distance_to_premises	• This variable is only calculated for Geographic Area 3, and refers to the Maximum distance from a premises to Access Node within the postcode sector. • The Network Cost model compares this variable to a threshold set in the model: if it is larger, 1:16 splitters are used for the postcode sector; alternatively, the standard 1:32 splitter is used. • The maximum distance for each premises is calculated as the sum of ug_infra_length_seg1 before de-duplication, plus the distance from the premises to the Splitter Location (as-the-crow-flies x 1.4, to estimate actual route distance), plus the distance from the premises to the nearest road.

Source: Cartesian

Quality Assurance

6.42 In the development of the Geospatial model, we performed several checks to assure the outputs are robust and to corroborate that the algorithms behaved as described above. Three types of reviews were made to this end:

     i.   Peer review of the scripts – Developers not involved in the creation of the scripts are engaged to review the code.

    ii.   Unit testing each module – The modules are tested in isolation. We included several check-points in the scripts of each module to compare the behaviour of the program against expected outcome.

   iii.   Sanity check of the results – A final analysis of the results is made to assure the program is performing correctly.

7 Infrastructure Module – Implementation and Assumptions

Overview

7.1   The Infrastructure module calculates the amount of new and existing physical underground infrastructure (e.g. ducts, sub-ducts, microtrench) required in Segments 1 and 2[21]. The module takes the relevant inputs from the Network Module, including Geospatial Model results, service demand inputs and coverage inputs, to dimension the physical underground infrastructure accordingly[22].

7.2   The modelled network will seek to reuse as much existing duct infrastructure (i.e. DPA services) as feasible, using the available capacity in existing ducts (input parameters for each network segment), and only build new duct when there is not enough capacity available in the existing ducts.

7.3   An overview of the logic of the Infrastructure module is shown in the figure below.

---

[21] As explained in this section, in Segments 1 and 2 we model three different levels of capacity (Red, Amber, Green) available in existing duct for new cables. In comparison, we use a simpler approach in Segment 3: we assume that existing ducts are either available to add all required cables (as usually only a small fibre cable is installed) or non-available at all (e.g. duct blocked). Therefore, as the Segment 3 infrastructure calculations are considerably simpler than for Segments 1 and 2, we included them in the Network module rather than the Infrastructure Module.

[22] We do not include overhead infrastructure (i.e. poles) in this module, as we assume that the existing aerial poles can support the fibre cables required to deliver the fibre services in scope.

Figure 19.   *High-Level Infrastructure Module Overview*
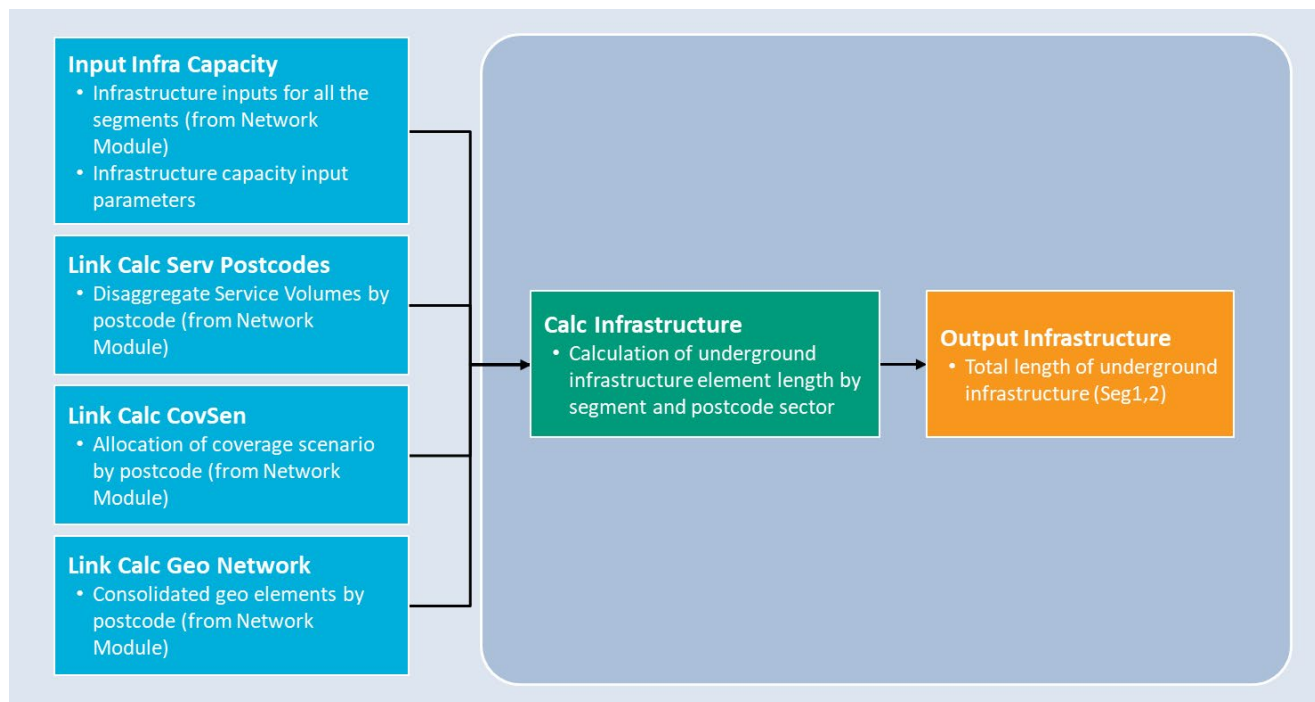
Source: Cartesian

Overview of Infrastructure Module Sheets

7.4   Input Sheets

- Input Infra Capacity

  Takes the key infrastructure input parameters for Segments 1 and 2 from the Network Module, e.g. existing duct capacity, duct surface type mix. This sheet also contains relevant infrastructure capacity input parameters (e.g. cable capacity of ducts).

- Link Calc Serv Postcodes

  This interface sheet takes the disaggregated service volumes by postcode from the Demand Module.

- Link - Calc CovScen

  This interface sheet takes the matrix of postcode sectors covered each year from the Network Module.

- Link Calc Geo Network

  This interface sheet contains the parameters from the Geospatial Analysis which are required to size the physical infrastructure components

7.5   Calculation Sheets

- Calc - Infrastructure

This sheet uses all the input sheets to calculate the underground Infrastructure length for segments 1 and 2, disaggregated by postcode sector.

7.6   Module Output

- Output – Infrastructure

    This sheet aggregates infrastructure lengths for all postcode sectors. These drivers are then used by the Network Module to dimension the relevant network components.
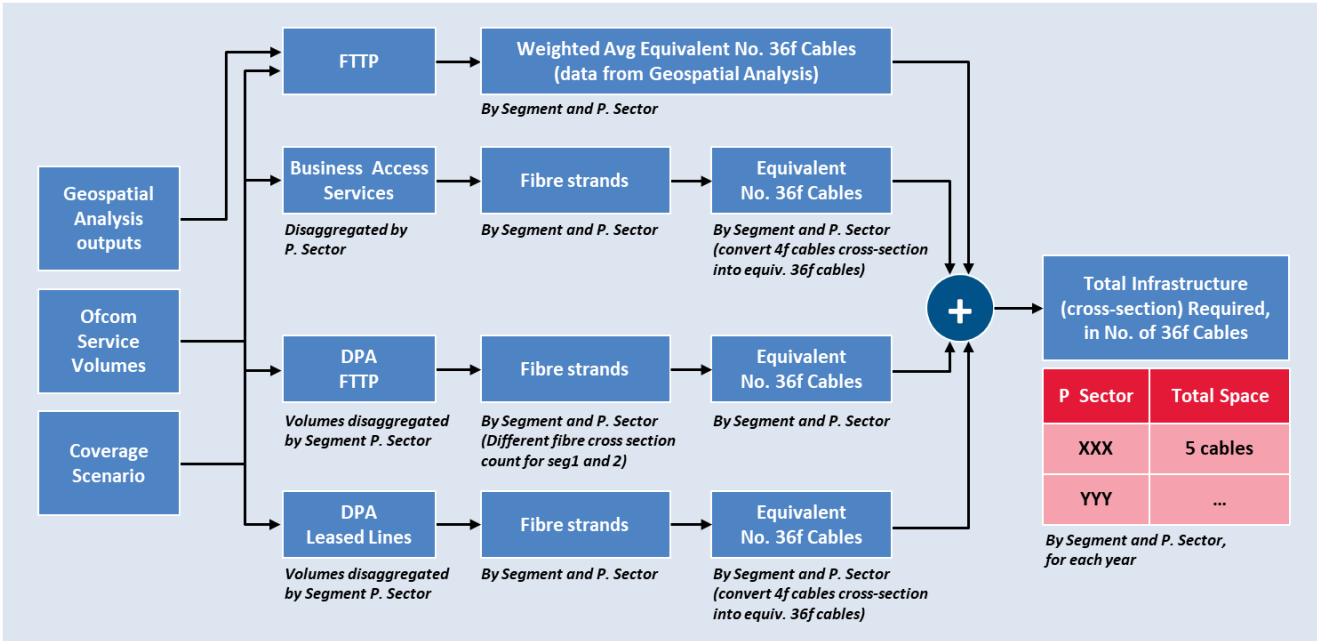
Approach to Underground Physical Infrastructure Dimensioning

7.7   The Infrastructure module first calculates the amount of fibre strands required by each service:

- FTTP: we assume fibre deployment for FTTP at Segments 1 and 2 are driven by coverage, i.e. the geospatial analysis calculates how much fibre is required at each postcode sector to reach all premises. Therefore, the infrastructure module uses the weighted average number of cables from the Geospatial Analysis (more details in Figure 18).

- Business Access Services: we include under this section all dedicated fibre services which terminate at business premises (e.g. EAD, EAD LA, Optical Service – Access, Dark Fibre – Access). We reserve space for a cable of 4 fibres for each subscriber (see description of the fibre element in Figure 20 for more details).

- DPA: see the DPA Technology section (paragraphs 4.17 - 4.19) for specific details on how much space should be reserved for fibres for each DPA service type (DPA FTTP Segment1, DPA FTTP Segment2 and DPA Leased Lines).

7.8   The model converts the number of fibre strands into the equivalent number of 36 fibre cables for each service. We then aggregate the number of cables to obtain the total number of 36 fibre cable equivalents (in terms of cross-sectional area) to deliver all services in scope. The diagram below provides a summary of the approach:

capacity tiers. In the example that we are following, we first calculate the length of underground infrastructure for each duct capacity tier (e.g. Red represents 10%, therefore 500m for postcode sector *XX X* (10% of 5,000). As discussed in paragraph 7.2, the model seeks to exhaust the capacity at existing ducts before building new ducts. Therefore, at each capacity tier, we determine how many cables can fit in existing ducts, and how many have to be installed in new ducts. As an example, in postcode sector *XX X* we need to fit five 36f cables: as the Amber tier has a spare capacity of three 36f cables, we exhaust the existing capacity, and we still need to build new underground infrastructure to fit two 36f cables.

- **D. Capacity parameters.** We define a set of capacity parameters in the model ('Input Infra Capacity' sheet) including the cable capacity of ducts (currently set to twelve 36f cables) and sub-ducts (currently set to three 36f cables), the surface type mix by geotype and segment (50% soft, 40% Footway, 10% Carriageway in the example), and the criteria to determine when to build new duct vs. microtrench: in the model we set that new duct (rather than microtrench) is required by default, unless an increment of only one new 36f cable is required in a postcode sector in a given year, in which case microtrench is used.

- **E. Underground Infrastructure Length**. We use the data from C and D in order to calculate the total length of underground infrastructure, for each postcode sector and year. In the example we are using, a total of 1,500m of new duct is required at postcode *XX X*: 500m from capacity tier Red, and 1,000m from capacity tier Amber. No microtrench is required as we need to fit more than one cable with new infrastructure. We use the same type of logic to calculate the length of existing duct, and the length of sub-duct which needs to be installed in existing duct[23].

- **F. Drivers for Network Model**. We calculate the total lengths of underground infrastructure each year, by summing the lengths of infrastructure in those postcode sectors that are enabled, as per the selected coverage deployment scenario. These lengths are then linked to the Network Cost model, which uses them to estimate the capex cost of these components.

---

[23] We note that CPs may choose to install cables in duct using sub-ducts, or directly. In Segments 1 and 2, we have assumed that sub-ducts are used, as we believe it makes the simplifies the identification and maintenance of the fibre cables. (in addition to providing additional protection).

7.10   The figure below illustrates the approach to calculate the underground infrastructure lengths:

Figure 21.   *Underground Infrastructure Dimensioning Approach – Segments 1, 2*
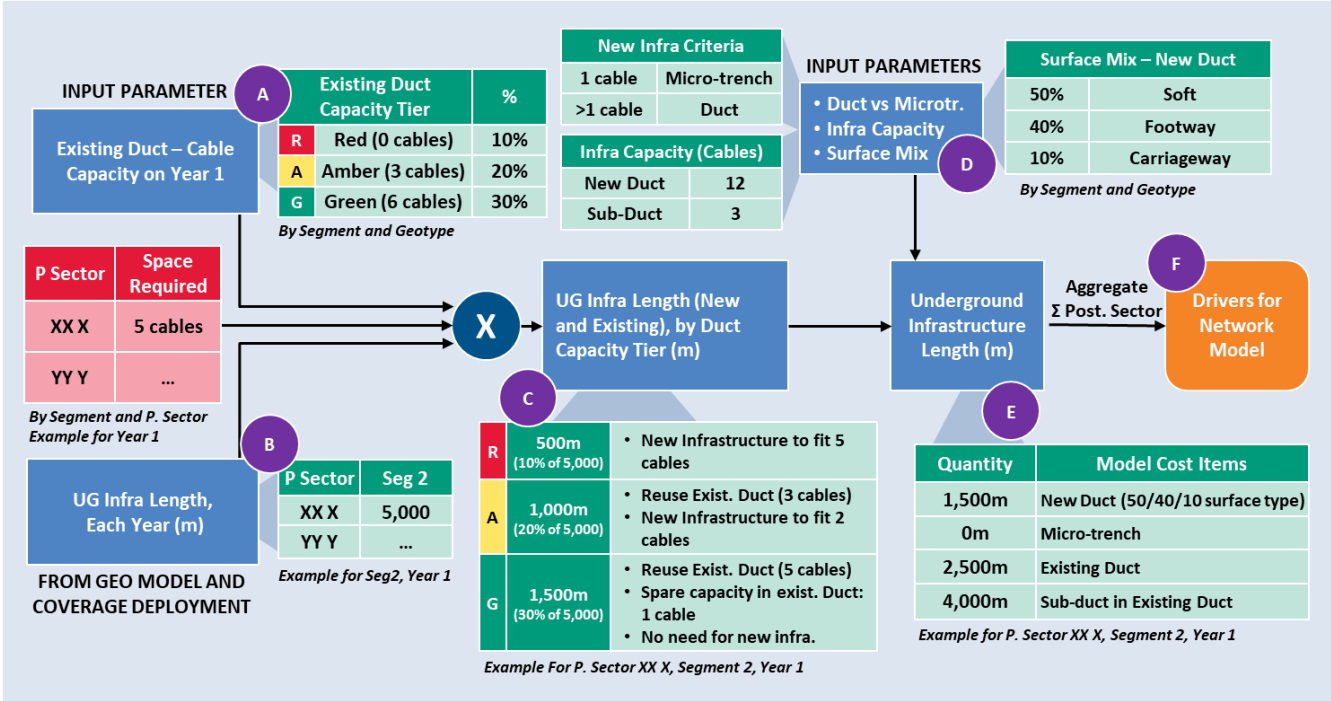
Source: Cartesian

8   Network Module – Implementation and Assumptions

Overview

8.1   The Network module takes the Geospatial Model results, the service demand and coverage inputs, and the outputs from the Infrastructure Module, to calculate the required number of network components. An overview of the logic of the network module is shown in the figure below.

Figure 22.   *High-Level Network Module Overview*
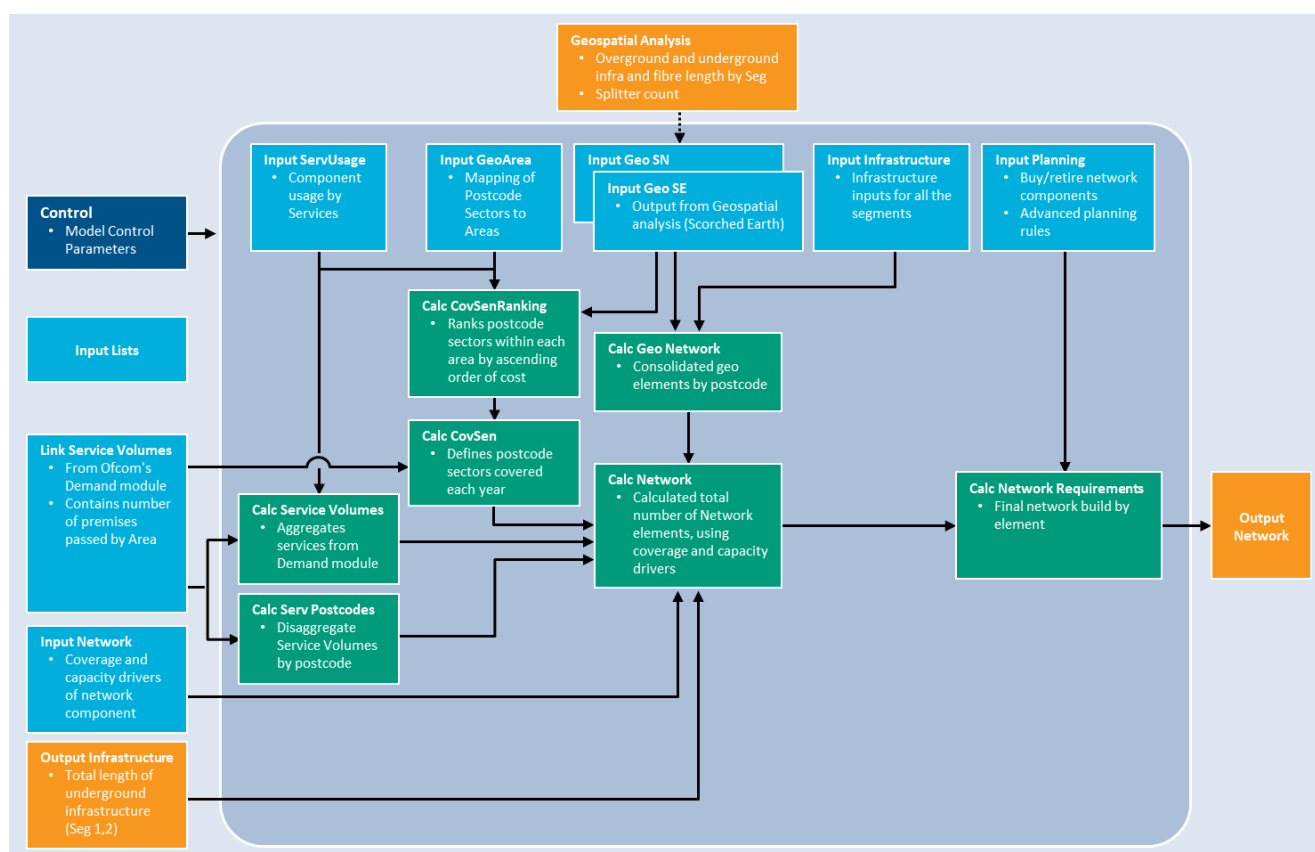
Source: Cartesian

Overview of Network Module Sheets

8.2   Input Sheets

- Control

  Shows key parameters which affect the overall model for scenario modelling and sensitivity analysis. These include the model parameters (e.g. Network Modelling Approach, Exchange Ethernet NTE Rack Capacity) as well as a number of sensitivity parameters (e.g. CPI). The control parameters are taken from Ofcom's Control Module.

- Parameters

Defines the three settings (low, medium and high) for variables that can be flexed in the model such as Egress Capacity Splitter and Capex Trend Categories

- Input Lists

This sheet lists the network elements, geo elements and drivers used in the model

- Link - Service Volumes

This interface sheet takes the service volumes from the Demand Module. It contains the number of premises passed by Geographic Area

- Input Infrastructure

This sheet contains the infrastructure input by segment and by geo-type, including split of overhead and underground fibres, percentage of new duct build by surface type and proportion of existing duct availability by segments.

- Off-model – Geospatial Analysis

See section 6 for details about the approach. The results are used by the Input Network sheet.

- Input GeoArea

This sheet contains the mapping of postcode sectors to Geographic Areas

- Input Geo SN

The output results of the Geospatial Analysis (Scorched Node)

- Input Geo SE

The output results of the Geospatial Analysis (Scorched Earth)

- Input – Network

This sheet contains the dimensioning drivers for each network element, which can be coverage drivers and/or capacity drivers

- Input – ServUsage

Determines which network elements are used by each service in the *Service Usage Factor* matrix. This is used in the Cost Recovery module to calculate the cost of each service.

- Input – Planning

This sheet includes the asset lives of all the network components and defines the asset replacement purchase rules as well as the advanced planning rules.

8.3   Calculation Sheets

- Calc - Service Volumes

This sheet aggregates the subscriber volume from Ofcom's Volumes Module, which will be used in calculating the subscriber related drivers. Additionally, it calculates the service volumes by network component, which output feeds into the Cost Recovery module.

- Calc – Serv Postcodes

This sheet calculates the number of subscribers in each postcode sector, which will be used for the correct dimensioning of the access network.

- Calc – CovSen Ranking

This sheet ranks the postcode sector within each area by ascending order of costs.

- Calc – CovSen

Defines the postcode sectors covered each year based on the premises passed provided in Ofcom's Service Demand volume.

- Calc – Geo Network

  Consolidates the Geo elements from selected Geospatial Analysis output (SN/SE)

- Calc – Network

  Using the input sheets described above, this sheet calculates the asset count of the NGA network elements.

- Calc – Network Requirements

  Using the network element volumes from *Calc_Network,* and the network planning rules from *Input_Planning,* this sheet calculates the total quantity of network assets that need to be purchased each year.

8.4   Module Output

- Output – Network

  This sheet reproduces the outputs of *Calc – Network Requirement* and is used as an input by the Cost Module.

Dimensioning of Elements - Modelling

8.5   The bottom-up model allows up to two drivers to determine the quantity of the element required:

- MinDriver is the minimum number of an element that is required by the network architecture, independent of demand (i.e. the minimum quantity of a network element that would be required if there was no network traffic).

- The Capacity Driver determines how the quantity of the network elements are scaled, i.e. units in excess of those computed as the 'MinDriver'. The capacity drivers are either (a) direct demand inputs (e.g. a function of traffic or lines); or (b) derived inputs (e.g. the number of network elements is derived from the quantity of another network element).

8.6   The coverage and capacity inputs are independent.

8.7   To simulate the capacity planning and implementation functions of a real-world operator, the bottom-up model incorporates a capacity utilisation threshold.

8.8   For most elements, we follow a common approach to determine the required quantity for each network element in each year of the bottom-up model. This approach is illustrated in Figure 23.[24]

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[24] The calculations of element quantities at step 3 in the diagram are interim results and care must be exercised if analysing these figures as they may appear inconsistent in isolation due to the sequence of calculations. On a standalone basis, only the final results (after calculating the maximum figure) are meaningful.

Figure 23. *Element Dimensioning Approach*
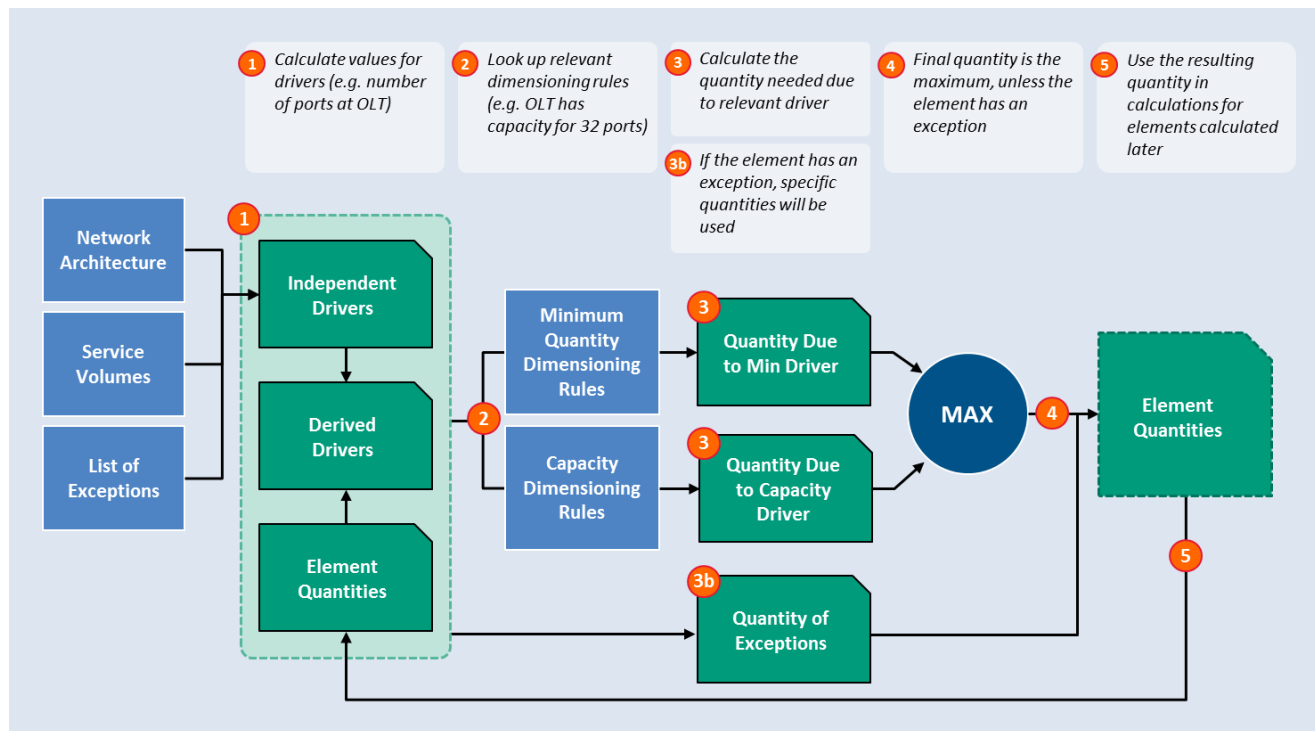
Source: Cartesian

8.9 The bottom-up model is also able to accommodate exceptions to the above approach. However, these exceptions are independent of the coverage and capacity inputs.

Calculate the Buy and Retire for Different Elements

8.10 Once the bottom-up model has calculated the total number of elements required, it calculates the additional quantities required in each year given advance-planning requirements, the elements purchased for additional capacity and those purchased to replace retired equipment.

8.11 The bottom-up model calculates the quantity of network elements retired. Assets in the network model are retired at the end of their useful lives and replaced if still required. As in real-world operations, there is variation between the useful lives of different network elements[25].

8.12 The bottom-up model is based on an annual assessment, and as such all lead times will be rounded to the nearest whole year. The bottom-up model assumes a planning lead time of one or zero years, depending on the network element. Those elements mostly driven by coverage drivers, which tend to require civil works and planning permission, are modelled with a planning lead time of one year. Other network elements requiring less planning and lead time for their installation are modelled with a planning lead time of zero years (i.e. less than six months).

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[25] We note that in the real world there might be some exceptions to the replacement rules, e.g. leased lines network terminating equipment. For leased lines, the model calculates the replacement capex for NTEs using service volumes from the Volumes module rather than applying the standard useful life approach.

9 Cost Module – Implementation and Assumptions

9.1 The Cost module takes its inputs from the Network module and produces total network capex cost estimates. The outputs from this sheet are then used as inputs in the Cost Recovery module. An overview of the cost module logic is shown in Figure 24.

Figure 24. *Cost Module Overview*
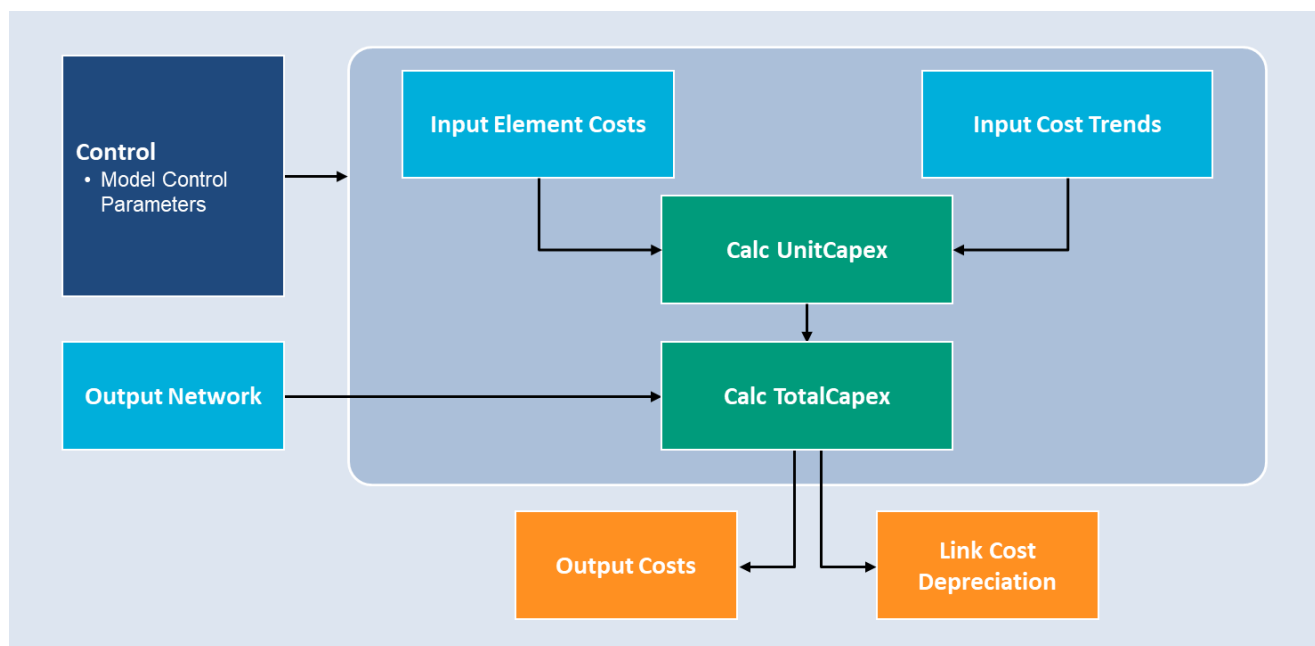
Source: Cartesian

Overview of Cost Module Sheets

9.2 Input Sheets

- Control

  Shows key parameters which affect the overall model for scenario modelling and sensitivity analysis. The control parameters are taken from Ofcom's Control Module.

- Input – Output Network

  This sheet contains the total asset count to be purchased each year and is used as an input sheet to calculate the total service costs.

- Input – Element Costs

  This sheet details the current unit Capex costs of all the network elements and is used in conjunction with the *Input Cost Trend* sheet to calculate the evolution of Capex unit costs over time.

- Input – Cost Trends

  This sheet contains the projected evolution of costs of the network elements (e.g. cost of active equipment tends to decrease overtime). These inputs are used in conjunction with *Element Costs* sheet to calculate the evolution of Capex and Opex unit costs over time.

9.3   Calculation Sheets

- Calc – UnitCapex

  Calculates the unit Capex cost of the network elements, using *Element Costs* and *Cost Trend* as inputs.

- Calc – TotalCapex

  Multiplies the Capex unit cost from *UnitCapex* by the number of network elements to determine the total Capex costs.

9.4   Output Sheets

- Output – Costs

  This output sheet summarises the total Capex costs incurred to deliver the full-fibre services. This sheet is used in the Cost Recovery module.

- Link – Cost Depreciation

  This output sheet contains output tables required by the Cost Recovery module for calculating the asset cost depreciation over time.

Unit Capital Costs

9.5   Unit costs in the Draft Model are placeholder values. These values will be updated in a future version of the model.

9.6   Installation costs are included in the unit capital costs. The asset retirement costs will be set to zero, as the model will assume that an asset is retired at the same time it gets replaced (thus effectively assuming zero retirement costs). This is because we would expect an efficient operator to align both tasks (in the majority of cases) in order to minimise costs and to keep a certain quality of service (i.e. the network operator would have to temporarily drop the service in the affected area if it were to separately carry out the retirement and replacement activities).

Element Unit Costs Trends

9.7   The bottom-up model calculates the unit capital costs of each network element over the life of the network.

9.8   In the Draft Model we used estimated nominal annual cost trends of each network element.

Calculation of Total Costs and Module Outputs

9.9   The total annual capital expenditure for each network element is calculated as follows:

- The product of that year's unit capex figures (including equipment and capitalised labour costs) and the number of network elements purchased in that year.

9.10   The total network Capex provides inputs to the Cost Recovery module. In addition to the total cost outputs, the element unit Capex trends, and element quantity outputs from the cost module are also used by the Cost Recovery module. Finally, the Service Usage factors from the Network module are also used in the Cost Recovery module to allocate the costs of network element output to network services.

10 Glossary

Abbreviation	Definition
Avg	Average
Calc	Calculation
Capex	Capital Expenditure
CCJ	Cable Chamber Joint
CPE	Customer Premises Equipment
CPI	Consumer Price Index
DF	Dark Fibre
DPA	Duct and Pole Access
EMST	Euclidean Minimum Spanning Tree
FTTC	Fibre To The Cabinet
FTTP	Fibre To The Premise
GE	Gigabit Ethernet
GEA	Generic Ethernet Access
GPON	Gigabit Passive Optical Networks
LL	Leased Line
MEA	Modern Equivalent Asset
MPF	Metallic Path Facility
MST	Minimum Spanning Tree
NTE	Network Termination Equipment
OCR	Optical Consolidation Rack
ODF	Optical Distribution Frame
OH	Overhead
OLT	Optical Line Termination
ONT	Optical Network Termination
Opex	Operational Expenditure
PON	Passive Optical Network
SQL	Structured Query Language
UG	Underground
UK	United Kingdom of Great Britain and Northern Ireland
WLA	Wholesale Local Access

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