BOTTOM-UP LRIC MODEL METHODOLOGY

A REPORT PREPARED FOR THE ILR

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CONTENTS

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1 Introduction

In its 2025 decision[1] analysing the wholesale markets for local and central access, the Institut Luxembourgeois de Régulation (ILR) concluded that POST Luxembourg has SMP in both relevant wholesale markets. As a result, the ILR imposes the following obligations on POST to promote effective competition in the retail market: (i) access, (ii) non-discrimination, (iii) transparency, and (iv) price controls on wholesale access products. With regard to price controls, the ILR introduces price caps for wholesale access to fibre.

To support price regulation on this market, ILR has engaged Frontier Economics to update the existing cost model in order to estimate the cost of a wholesale fibre unbundling product.

This document sets out the methodologies, inputs and assumptions used to implement the bottom-up long run incremental cost model (BULRIC) of a hypothetical efficient operator (HEO) in Luxembourg. It should be read as a complement to the model's *specification* document presenting the context, the characteristics of the HEO and an overview of the methodological considerations.

1.1 Structure of the model

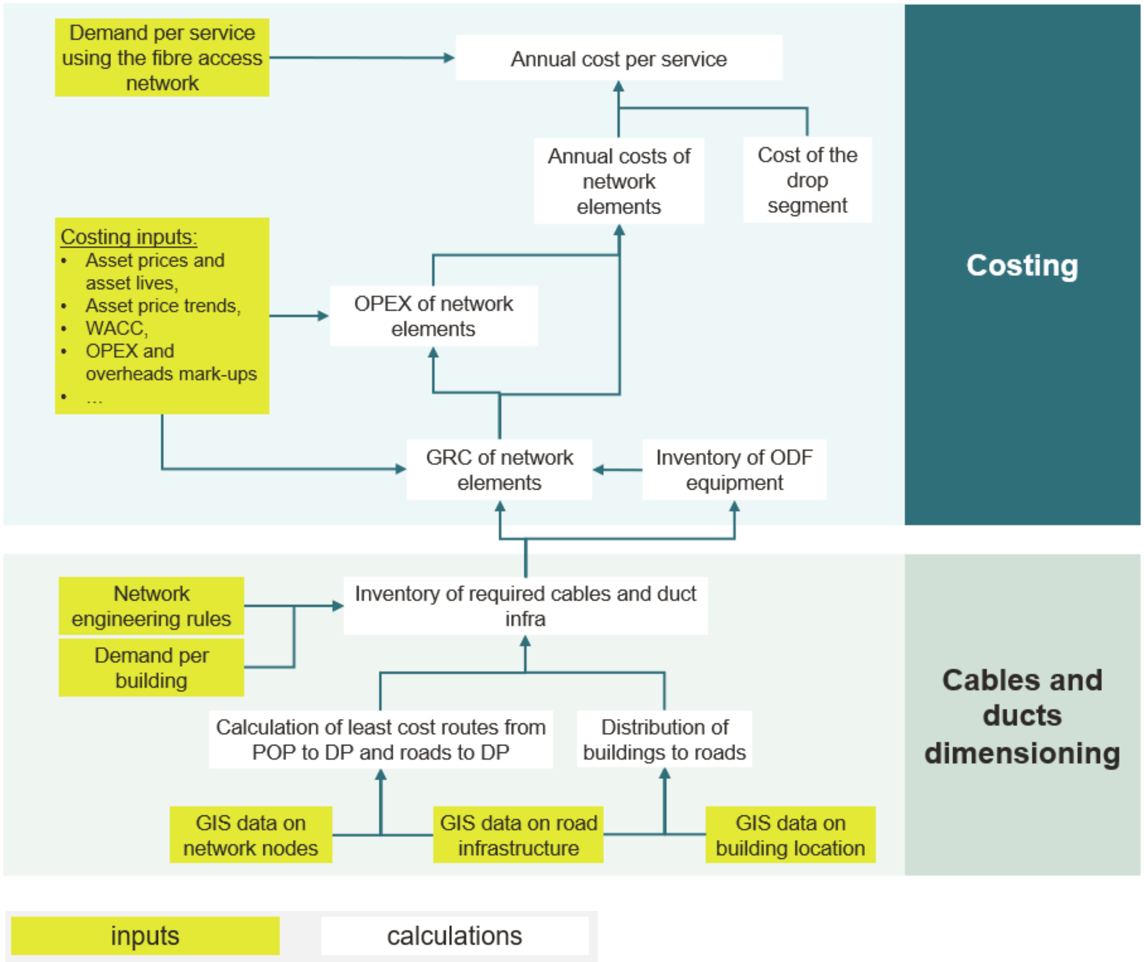
As described in section 2 of the model's specification document, the proposed structure of the model consists of two main modules:

- A *cables and ducts dimensioning* module, which determines the inventory of fibre cables and physical infrastructure in the access network;
- A *costing* module, which calculates the costs of the different elements used in the provision of the fibre unbundling product.

[1] Règlement ILR/T25/1 du 30 septembre 2025 portant sur la définition du marché pertinent de la fourniture en gros d'accès local en position déterminée (marché 1/2020), l'identification de l'opérateur puissant sur ce marché et les obligations lui imposées à ce titre, https://legilux.public.lu/eli/etat/leg/rilr/2025/09/30/a418/jo

Règlement ILR/T25/2 du 30 septembre 2025 portant sur la définition du marché pertinent de la fourniture en gros d'accès central en position déterminée pour produits de grande consommation (marché 3b/2014), l'identification de l'opérateur puissant sur ce marché et les obligations lui imposées à ce titre, https://legilux.public.lu/eli/etat/leg/rilr/2025/09/30/a419/jo

Figure 1 Modules, Inputs and Calculations used in the bottom-up model



The *cables and ducts dimensioning* module is built using Python. The *costing* module is built using Excel and uses the outputs of the first module.

1.2 Structure of the methodology document

The rest of this document sets out how the approach described in the model specification document is implemented in practice. In particular:

- Section 2 describes the *Cables and ducts dimensioning* module;
- Section 3 describes the *Costing* calculations.

2 Cables and ducts module

The *cables and ducts* module is split into four sub-modules summarised in the table below and further described within this section. The output of this module is a set of tables summarising the inventory of cable and duct equipment of the HEO.

Table 1 Overview of sub-modules

Sub-module	Description	Core scripts
Pre-processing	Converts raw GIS and tabular inputs into structured datasets used in downstream steps. Outputs a connected road graph and structured tables describing premises, Distributions points (DPs) and Points of Presence (PoPs).	■ **pipeline.py**: orchestrates pre-processing steps ■ **gis.py**: builds road graph (segment, node creation, connectivity bridging) ■ **tabular.py**: processes premises, DPs, PoPs from raw files; generate IDs, coordinates, and household/business counts ■ **nearest_node.py**: snaps each premises, DP, PoP to nearest road graph node ■ **base.py**: shared helpers (logging, utilities) ■ **data.py**: reads, writes and catalogues processed outputs
Houses-to-Roads	Allocates every premise to a specific road segment and side. Counts buildings, households and businesses per [road segment, side].	■ **houses_to_roads.py**: maps buildings to road segments and assigns side of street.
Least cost routing (LCR)	Computes the shortest routes on the road graph: ■ from road nodes to the nearest DP and, ■ from DPs to their serving PoP.	■ **lcr.py**: builds graph, runs Dijkstra shortest-path search, and exports per-node distance tables, including road segment list.

Sub-module	Description	Core scripts
	Outputs distances from road nodes to parent node (DP or PoP) and the set of road segments in each route split.	
Cable and Duct	Calculates the cables and ducts inventory in three network segments: ■ Access – road segments where buildings are located; ■ Distribution side (D-side) – between access road nodes and DPs; ■ Exchange side (E-side) – between DPs and PoPs. Outputs are consolidated by geotype and cable type.	**stages.py**: defines the sequence of calculations Calculations: □ **access.py**: access fibre/duct logic □ **distribution.py**: distribution fibre/duct logic □ **eside.py**: exchange fibre/duct logic □ **infrastructure.py**: duct allocation, trenching, house density, geotypes □ **inventory.py**: inventory of assets

Source: Frontier Economics

Configuration & execution

The module can be run using the *pipeline.py* orchestrator file which executes the sequence of sub-modules and writes the output of each step in a timestamped Excel inventory located in the output folder.

All parameters of the calculations are read at runtime from the *run_config.toml* file.

The following sections describe the sub-modules in more details.

2.2 Data pre-processing

This step prepares the key elements used by downstream calculations:

- a connected road graph with all road segments along which the network can be deployed;
- the set of building addresses where demand is located; and
- the concentration points (DPs and PoPs) around which the network is built.

2.2.1 Road network GIS Processing

Inputs

The model assumes that the network of the HEO can be deployed along existing roads in Luxembourg. It relies on the roads described in the Transport Network layer of the *B-DL GeoBase*[2].

Methods

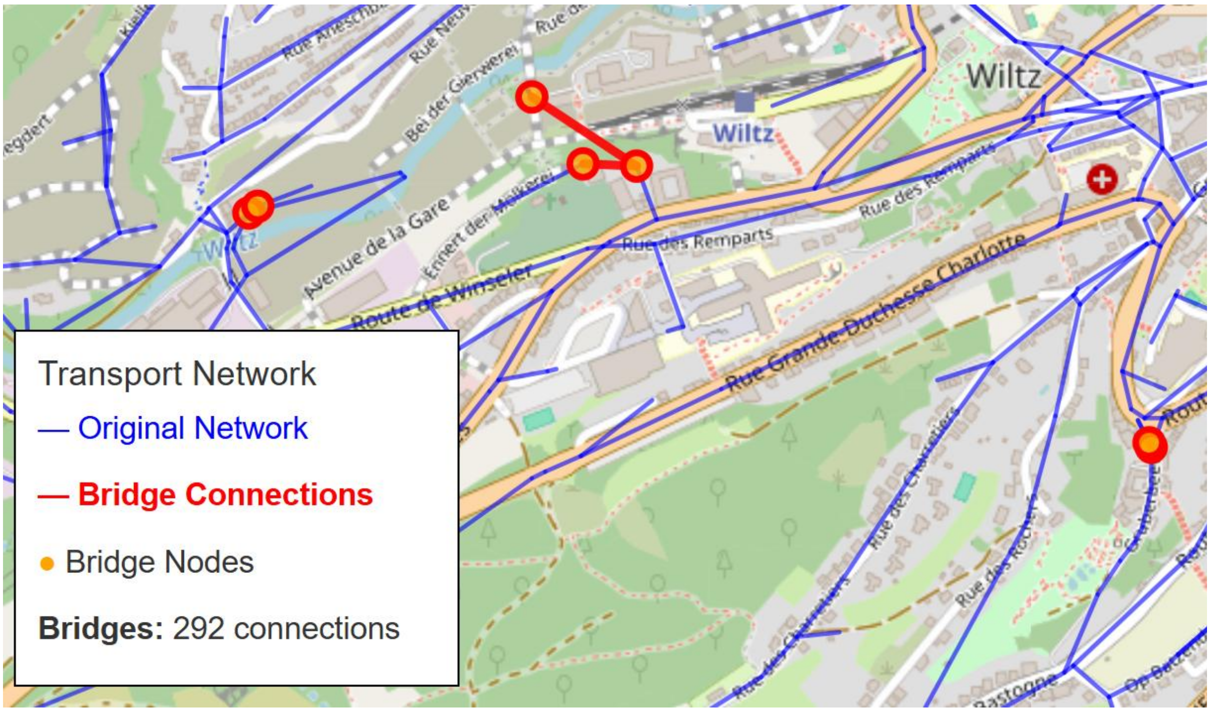
- **Segment extraction.** Roads are stored as MultiLineString geometries in the *B-DL GeoBase*. We disaggregate them into single LineString segments and assign a unique line ID to each road segment.
- **Node creation.** For every road segment we extract the “start” and “end” coordinates, create nodes at those endpoints, and de-duplicate them to form the node set.
- **Graph build.** The resulting segments and nodes define the network graph used by routing, duct dimensioning and cable sizing.
- **Connectivity bridging.** The road network graph obtained has small gaps leading to isolated segments, i.e. roads which are not connected to the rest of the network. To ensure that every premise can reach its nearest DP, isolated nodes are connected to the nearest connected node by adding straight-line “bridge” linking up to a maximum gap of 500 m (see figure 4 below). These “bridges” are introduced to ensure continuity if connectivity where gaps are detected.

Output

The steps produce a complete road network graph along which cables and ducts can be installed.

[2] The BD-L-GeoBase is the official reference for geographic vector data produced by the Administration du Cadastre et de la Topographie for the entire territory of the Grand Duchy of Luxembourg: https://data.public.lu/fr/datasets/bd-l-geobase/

Figure 2 Example of GIS bridging



Source: Frontier Economics

2.2.2 Pre-processing of addresses and fibre network nodes inputs

This step converts inputs from building addresses and POST fibre network node inputs in a standard format.

- **Addresses** are described in the *RGDR_ShareTelecom.csv* file. Coordinates are converted to LUREF EPSG:2169. We keep address ID, counts of households and business occupants, and building coordinates. Records with missing or zero values are dropped.
- **Fibre network nodes** are described in *dps.csv*[3] and *pops.csv*. IDs are normalised, coordinates are validated, and duplicates are removed. Only rows with valid geometry are retained.

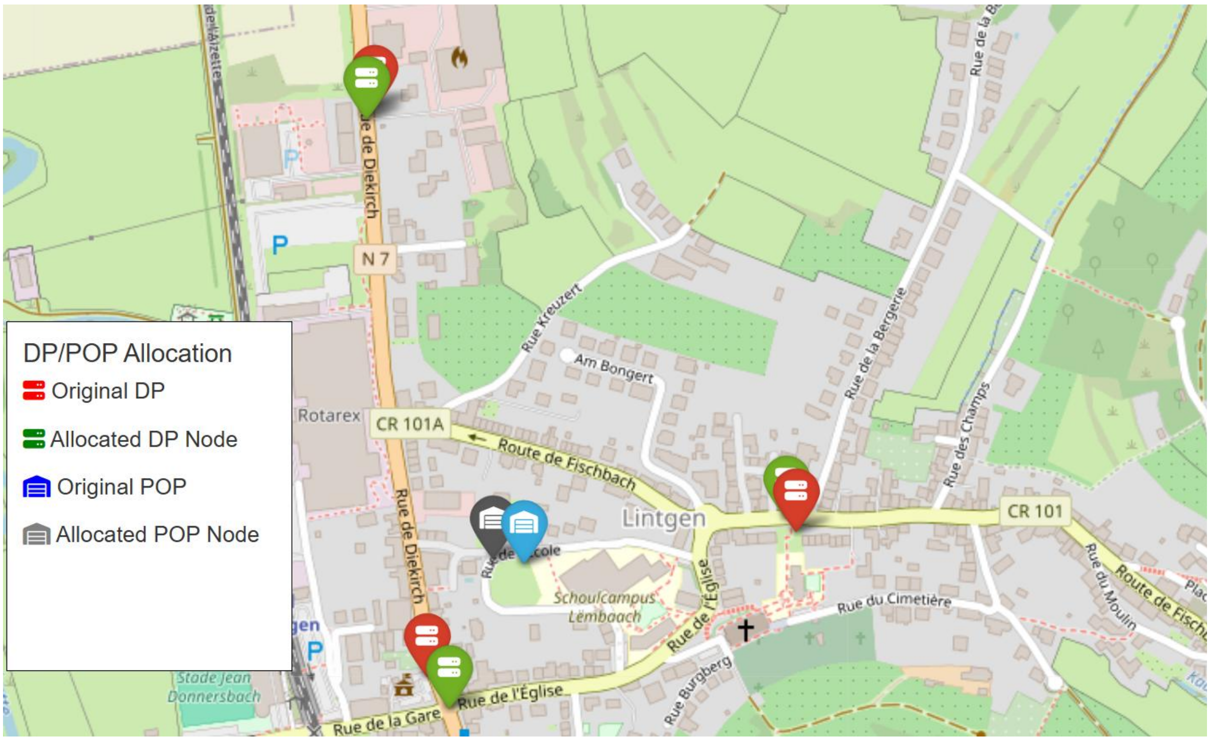
[3] The dimensioning of the network relies on a scorched node approach which considers DPs actually deployed by POST. POST's dataset of DPs for its P2P fibre network does not provide full national coverage, as certain regions remain outside the P2P footprint. To address this gap and ensure DPs are available across the national footprint of the HEO, two alternative DP datasets have been tested: (i) a hybrid dataset: POST's P2P fibre DPs supplemented by POST's copper DPs in areas not covered by fibre; (ii) the copper dataset: POST's copper DP dataset, which is assumed to provide

2.2.3 Mapping addresses and fibre network nodes to nearest road network nodes

This step attaches each address, DP and PoP to its nearest road graph node using straight-line distance.

Examples of this mapping are shown in Figure 3 below.

Figure 3 Illustration of DP and PoP mapping to road network



Source: Frontier Economics

Note: "Original DP" is located at coordinates described in the dps.csv file, "allocated DP node" is the nearest node on the road network graph

2.3 Houses-to-Roads

This step assigns each building address to the nearest road segment and to a side of that segment. It then aggregates demand per road segment and side. The result feeds into Access, Distribution side (D-side) and Exchange side (E-side) calculations.

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national coverage. The results indicate that the choice of DP dataset do not materially affect the inventory of assets modelled.

Inputs

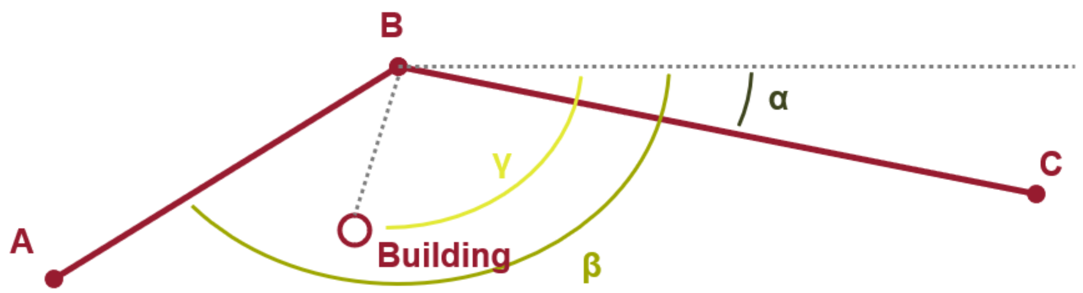
This step relies on the road network processed in 2.2.1 and addresses processed in 2.2.3.

Method

- **Orientation of road segments.** For every road segment, we calculate its orientation. The angle is computed using the arctangent function, which returns a value in radians between –π and +π[4].

- **Angle from road node to building.** For each building, we determine its nearest road node and compute the orientation of the segment from that road node to the building (also using arctangent).
- **Match building to a road segment.** For each building, we compare the orientation of the [nearest node to building] segment with that of all road segments connected to the nearest node. We select the segment with the closest orientation (see Figure 4 below). If two segments tie, we select the one with the smaller *line id*.
- **Assign side of the road.** We then determine whether the building lies to the left or the right of the segment, we set side at +1; if to the right, we set side at −1.
- **Aggregate results.** Finally, for each road segment and side we count all buildings and verify that these totals match the input data, ensuring every building is assigned exactly once.

Figure 4 Illustration of road segment identification for each building



Note: road node B is the nearest to the building. We calculate the angle from B to the building (γ) and compare it with the orientations of the road segments (α for BC, and β for BA). The angular difference | β - γ | is smaller for segment AB than for segment AC | α - γ |, so the building is associated with segment AB.

[4] This correspond to - 180° to +180° in degrees.

Output

The output is a table with the following information: *line id*, *side*, *number of buildings*, *number of businesses* and *number of households*.

2.4 Least-cost routing (LCR)

This step builds the routes used to deploy the fibre network. This is done by running a least-cost routing algorithm twice:

(i) from road nodes (road segment endpoints) to nearest DP, and

(ii) from DPs to PoPs.

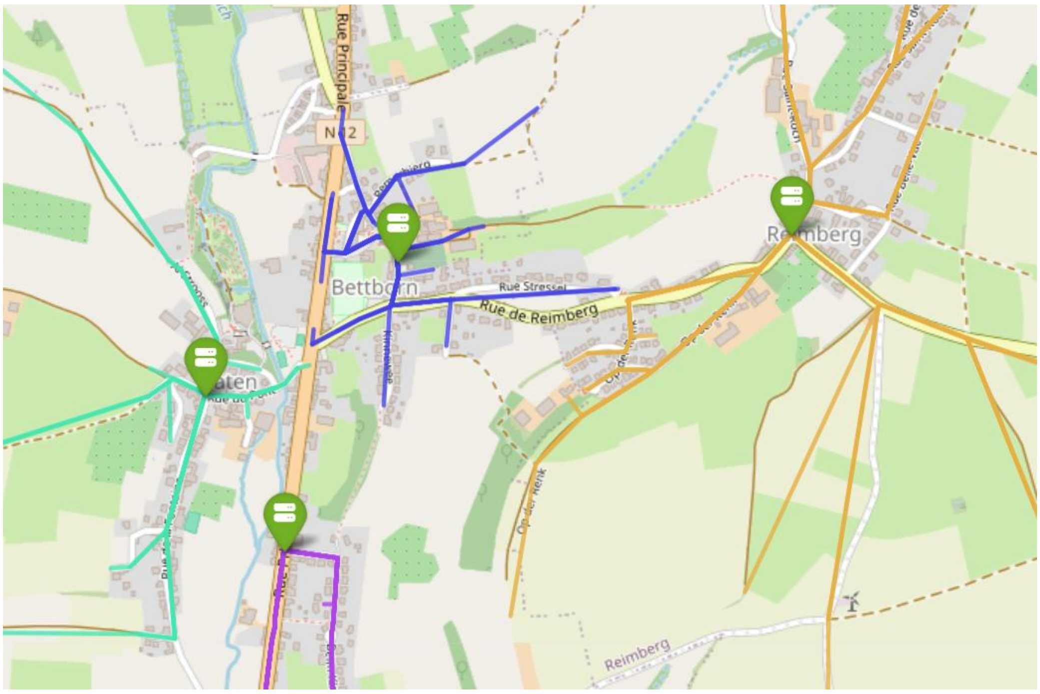
Inputs

- Road graph: list of road segments (line id, “start” node, “end” node, length).
- DP nodes: list of DPs attached to road nodes.
- PoP nodes: list of PoPs attached to road nodes.

Methods

- **Graph construction.** If multiple segments connect the same pair of nodes, we keep the one with the shortest length.
- **Least cost route: road nodes to nearest DP.** We run the Dijkstra algorithm with all DP nodes as sources. For each road node, we determine the nearest DP node.
- **Least cost route: DPs to PoPs.** We run the same algorithm and for each DP, we determine the nearest PoP node.
- **Integrity checks.** We then verify that: (a) all DP nodes have an associated PoP; (b) all road segments have an associated DP.

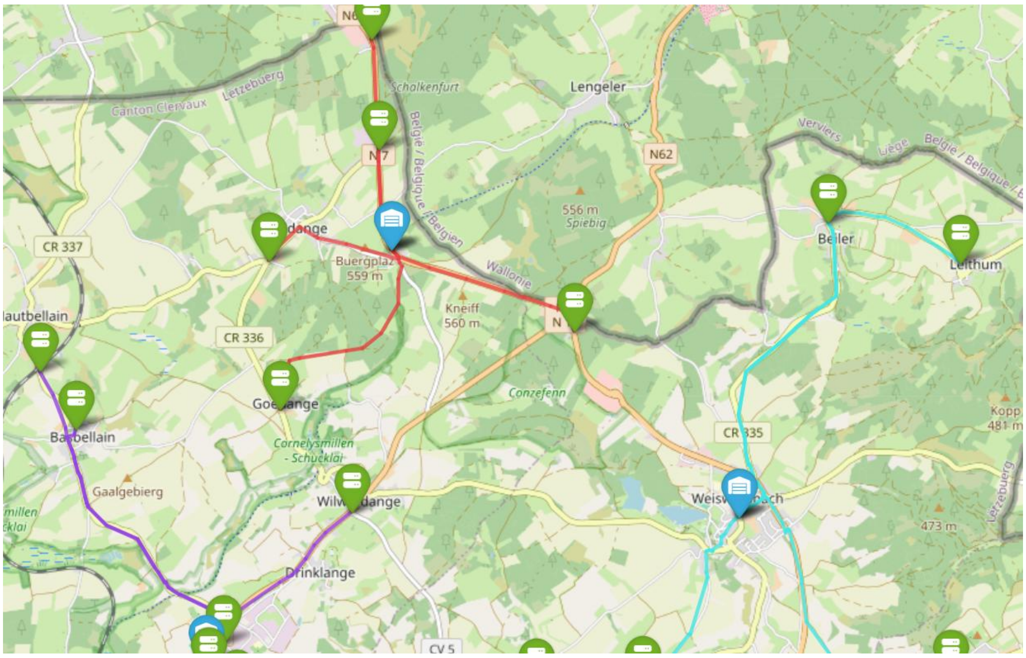
Figure 5 Least cost routes – DPs



Source: Frontier Economics

Note: Least cost routes (coloured lines) from street segments mapped to their nearest DPs (green indicators)

Figure 6 Least cost routes allocation – PoPs



Source: Frontier Economics

Note: Least cost routes (coloured lines) from DPs (green indicators) to PoPs (blue indicators)

Each run creates a *nodes* table (distances, nearest parent) and a *routes* table (set of road segments).

2.5 Cable and Duct requirements

This step calculates fibre cables, ducts and trenches needed on each road segment. Engineering parameters are read from *run_config.toml* (e.g., fibre cable sizes, geotype thresholds, D/E-side cables per duct, E-side fibres per cable, etc).

The calculations are organised into five parts:

- Access (A)
- Distribution side / D-side (D)
- Exchange side / E-side (E)
- Infrastructure (I)
- Inventory (INV)

2.5.1 Access

- **A1 – Fibre demand.** For each pair [road segment, side], we calculate the number of fibres required to serve demand in the corresponding buildings using counts of households and business occupants and parameters of number of fibres per household and business[5].
- **A2 – Cables.** We determine the smallest cable size (number of fibres) that meets the volume of fibres on each [road segment, side].
- **A3 – Ducts per road segment**. We determine whether a duct is needed to access houses on one or both sides of each road segment.
- **A4 – Houses on secondary side.** Where both sides require access duct, we identify the side with the smaller building count as the secondary-side.

2.5.2 Distribution side (D-side)

- **D1 – Route**. For each road segment, we compare the DP distance at both endpoints. The endpoint with the shortest distance to the DP is the parent node.

[5] In line with POST's P2P fibre rollout approach, the model assumes that the HEO deploys four fibres per SDU and four fibres per business premise. For SDUs, two fibres are connected end-to-end to the POP, while for business premises all four fibres are connected end-to-end.

- **D2 – Fibre and sizes.** For every road segment, we determine the number of fibres and size of fibre cables needed.
- **D3 – Duct number.** We calculate the number of D-side ducts per road segment using the D-side cables-per-duct parameter.

2.5.3 Exchange side (E-side)

- **E1 – Fibre demand per DP.** We aggregate all fibre demand at each DP.
- **E2 – Fibre cables per DP.** We calculate the number of cables to serve the number of fibres identified in E1.
- **E3 – Fibre cables per road segment.** We calculate the number of fibre cables per road segment in the E-side network by aggregating the number of cables to serve all DPs.
- **E4 – Ducts per road segment**. We calculate the number of E-side ducts per road segment using the E-side cables-per-duct parameter.

2.5.4 Infrastructure consolidation

- **I1 – Ducts per road segment.** We aggregate volumes of D-side and E-side ducts determined in the previous step to get the total number of ducts needed per road segment.
- **I2 – Share of trench costs per duct.** Where a road segment is used for routes used for distribution and exchange levels, the cost of the trench housing the ducts is split in proportion to the number of ducts.
- **I3 – Houses per road segment.** We calculate the number of buildings on each road segment.
- **I4 – House density per road segment.** We calculate the density of buildings along each road segment based on the length of the road segment and the number of buildings.
- **I5 – Road segment geotype.** We assign a geotype to each road segment based on geotype thresholds defined in the configuration file.
- **I6 – Secondary trench.** We calculate the length of secondary-side trench to serve buildings on the secondary side of the road.

2.5.5 Inventory – Excel outputs

These queries produce outputs in .xlsx format for export to the costing model. They summarise the inventory of ducts and cables modelled.

- **Access fibre**: total length by cable size; average length by cable size;
- **D-side fibre**: total length by cable size;
- **E-side fibre (type/total)**: counts by type and total cable length;
- **Duct lengths**: total Access / D-side / E-side ducted metres from per line counts;

- **Primary trench by geotype**: trench length on primary sides by geotype;
- **Secondary trench by geotype**: trench lengths and number of trenches;
- **Customer mappings**: volume of buildings, businesses, households per DP and per PoP.

3 Costing Module

The table below summarises the sheets in the costing module. The input data used in these sheets and the calculations are described in further detail in the following subsections.

Table 2 Costing module worksheets

Worksheet	Description of input data/calculations
Results	Summarises the cost estimates
Parameters and assumptions	Allows the user to select different parameters and modelling approaches and to visualise how it impacts the results of the model
Demand	Estimates demand forecast for fibre access services that the HEO is expected to serve
Equipment inventory & unit cost	Summarises the inventory of assets from the *Cables and ducts* module and calculates the unit costs for cables, ducts and trenches
ODF inventory	Determines the number of ODFs to serve demand in each PoP
Capex and OPEX	Calculates the total gross replacement costs (GRC) and operating expenditure (OPEX) for all modelled equipment
Capex annualisation	Calculates annual capital costs for the modelled GRC calculated in the previous sheet
Cost per asset class	Aggregates costs per asset class and calculates the total annual costs using different approaches (BULRIC or hybrid BULRIC and regulatory asset base)
Product costing	Calculates fibre access cost per line
Drop segment	Calculates the cost of the drop segment, i.e. the portion of the access network that connects the access road segments to the NTP at the end-user premises
Cable and Infra length	Inputs from the *Cables and ducts* module
POPs	Inputs from the *Cables and ducts* module
DPs	Inputs from the *Cables and ducts* module

3.1 Cables and ducts module outputs

The outputs of the *Cables and ducts* module are pasted in sheets *Cable and Infra length*, *POPs* and *DPs.*

3.2 Results

The main output of the model is the monthly cost of wholesale fibre loop unbundling per line.

We understand that the total costs of the line is recovered through a recurring monthly rental, i.e. there is not a dedicated "connection" product through which POST can recover some customer specific costs, such as those incurred to build the drop segment for its fibre network. We therefore also calculate the monthly cost of fibre loop unbundling per line including the drop segment.

These costs are calculated in real terms in 2025 euros and in nominal terms assuming inflation in line with ECB's target (i.e. 2%)[6].

3.3 Parameters and assumptions

The parameters and assumptions defined in this worksheet feed into the model and impact the overall results, which are recalled at the top of the worksheet. This enables the user to consider how the model results change following a change to these inputs.

The key inputs used are discussed in the following subsections.

3.3.1 Weighted average cost of capital (WACC)

The real pre-tax WACC is a key parameter in the annualisation formula which is determined by the ILR.

3.3.2 NGA Risk Premium

An NGA-specific risk premium can be added to ILR's reference WACC estimation. This parameter relates to the European Commission's Gigabit Recommendation, which provides that "*When setting access prices to VHCNs, NRAs should consider applying, in addition to the applicable WACC, a risk premium to reflect any additional and quantifiable risk of the new investment network project, including of newly built civil-engineering infrastructures, incurred by the SMP operator*".

[6] https://www.ecb.europa.eu/mopo/strategy/pricestab/html/index.en.html

3.3.3 Trench sharing

This parameter reflects the fact that when multiple utilities lay ducts in a trench, the cost of the trench is allocated between them based on the number of ducts.

For the base case, the model relies on the estimates provided by POST in its response to the information request.

3.3.4 Trenching costs

This parameter reflects that the cost of civil works may vary depending on the environment and in particular with the building density.

For the base case, the model relies on the estimates provided by POST in its response to the information request.

3.3.5 Cost of jointing chambers

Similar to trenching costs, the cost of jointing chambers may vary depending on the geotype, reflecting differences in ground conditions, construction methods, and permitting requirements.

For the base case, the model relies on the estimates provided by POST in its response to the information request.

3.3.6 Operating expenditure (OPEX)

The estimation of OPEX for fibre access networks in cost models generally follows two main approaches:

- OPEX mark-up, expressed as a percentage of the GRC of network assets based on mark-ups used in other models; or
- OPEX per line, based on operator-reported costs and information from other comparable jurisdictions.

3.3.7 Asset working lifetimes

To annualise GRCs, the model relies on asset lifetime assumptions for each asset class. These lifetimes were primarily informed by POST's response to Frontier's information request. We then validated these values by comparing them against benchmarks drawn from other European regulatory cost models, ensuring that POST's input is aligned with established regulatory practice.

3.3.8 Asset price trends

The model incorporates asset price trends for the following main asset categories: ducts and trenches, fibre cables, and optical distribution frames (ODFs). These price trends influence the evolution of the GRC over the forward-looking horizon of the model.

3.3.9 Common cost mark-up

A mark-up is applied in the model to allocate common costs according to LRIC+ principles.

3.3.10 ODF dimensioning and costing parameters

While an ODF may technically contain a large number of ports, not every port can be assumed to be available for active customer connections. This is because ODF allow sufficient patching space for rearrangements, and growth. Therefore, we apply a utilisation factor.

In addition to the ODF hardware equipment, we also account for the cost of the space required to install the ODF units in the PoPs.

3.3.11 Demand for the HEO modelled

The calculation of a cost per line requires assumptions on service demand over the modelled period. Consistent with the objective of modelling an HEO using only a P2P network, the model must reflect the level of demand that such a network would realistically serve.

There is no reason to expect that overall broadband demand in Luxembourg would be lower under a fully P2P network than under today's mix of technologies. Broadband penetration and usage are primarily driven by end-user needs for connectivity, not by the underlying access technology. Accordingly, we assume that the HEO serves the total broadband demand currently observed on POST's network across all technologies (copper, VULA, and fibre).

3.3.12 Drop Segment

The cost components of the drop segment installation include labour, material and transport costs. We assume that duct infrastructure costs for the drop segment are incurred by the building owners or developers.

For labour costs, the parameters are the estimated duration of the different tasks required to build the drop segment and on the cost of labour.

For material costs, we rely on an estimation of costs per installation.

For transport costs, we rely on the cost of a vehicle per km and the average number of km travelled by the field engineer to perform the installation.

These parameters are based on the 2023 drop segment model developed by Arcep and adjusted to reflect the specificities of Luxembourg.

For the volume of single-dwelling units (SDUs) and multi-dwelling units (MDUs) where a drop segment is installed, we rely on the building inventory described in Luxembourg's Geoportail database.

3.4 Demand

This tab forecasts the demand for total active lines on the HEO network.

3.5 Equipment inventory & unit cost

This sheet first adjusts the raw asset inventory from the *Cables and ducts* module using fibre roll-out parameters reported by POST. These parameters account for engineering realities that mean the actual quantities of equipment required are greater than the theoretical minimum.

In particular, these parameters are applied to reflect:

- Bends and routing constraints: fibre cables rarely follow perfectly straight paths; additional lengths are needed to accommodate bends, curves, and routing around obstacles.
- Splitting and splicing: extra fibre is required to allow for the processes of splitting and splicing, which is required to connect fibre cable segments.
- Reel-end wastage: a portion of fibre at the end of reels is typically unusable, meaning more fibre must be purchased than the nominal length of the network would suggest.
- Road crossings: this refers to how much more expensive it is to build "reinforced" trench segments where trenches cross roads. These segments require enhanced engineering and materials to support the weight of heavy vehicle traffic, making them more expensive than standard trenching.

We then estimate unit costs for relevant equipment using POST's inputs on (i) equipment and installation costs and (ii) additional costs related to micro-ducts, splicing and jointing.

3.6 ODF inventory

This sheet calculates the number of ODFs needed at each POP to allow for patching of all fibre lines installed at corresponding customer premises. This is estimated by dividing the number of fibre lines connected at each ODF by the utilisation factor of an ODF and the size (number of fibre connectors) of an ODF.

3.7 Capex and OPEX

This sheet calculates two main outputs:

- Total GRC for each type of equipment in the modelled network. This is calculated by multiplying the unit GRC of each type of equipment by the number of pieces of equipment required as determined in the *Equipment inventory & unit cost* sheet.
- Operating costs which are estimated using the approaches set out in section 3.3.6.

3.8 CAPEX annualisation

This sheet takes the total GRC figures for each equipment type, as calculated in the previous sheet, and derives annual capital costs for each type of equipment. This is based on an annuity formula which considers the following inputs defined in section 3.3:

- WACC (real pre-tax, including risk premium);
- Price trends (in real terms); and
- Working life of assets.

Figure 7 Annual capital charge calculation formula

$$Annual\ capital\ charge = GRC * \frac{(WACC - price\ trend)}{1 - (\frac{1 + price\ trend}{1 + WACC})^{Asset\ life}}$$

Notes:

This function is directly derived from expression to calculate the present value (PV) of the n (asset life) charges discounted at WACC. By construction, the modelled operator therefore recovers the full GRC over the asset life.

The price trend tilts the charge path in line with expected asset price movements. If price trend is > 0, charges rise each year, shifting recovery to later years in line with higher future replacement costs. If price trend <0 (price erosion), charges are front-loaded (still NPV-neutral) so the operator is not left under-recovered as replacement costs fall.

3.9 Cost per asset class

This sheet calculates the annual costs per asset class[7] and the total costs for all assets including common costs.

[7] The regulatory asset information provided by POST for reusable assets was not sufficient to implement a reliable RAB valuation approach so we have applied a BULRIC to all assets.

3.10 Drop Segment

This sheet first estimates the installation costs of building the drop segment for all SDUs and MDUs in Luxembourg using inputs described in section 3.5.

The monthly cost of the drop segment per line is then obtained by:

- annualising these installation costs,
- dividing these by the number of total active lines, and
- adding OPEX and common costs mark-ups.

3.11 Product costing

This sheet calculates the fibre loop unbundling per line using the total costs of the access network calculation in the *Cost per asset class* sheet and the total active lines on the HEO network estimated in the *Demand* sheet.