The Impact of Geography and Demography on the Economics of Fibre Optic Access Networks

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Abstract—**This article presents a study relative to the influence that demographic and geographic conditions have on the economics of fiber optic telecommunications access networks. This approach differs from other studies by merging classical techno-economic evaluation methods with geographic engineering tools and models. This analysis is part of a project to identify the costs of all type of utilities´ infra-structures as a function of the degree of urban dispersion. The work presented in this paper is the quantification of a PON network using an approach that combines fiber optics engineering and deployment with geographic tools.**

Keywords- GPON techno-economics; access network fiber deployment; urban dispersion; local scale; utilities.

I. INTRODUCTION

Today´s cities are quite different from the past. The continuous geographical expansion of the utilities' infrastructures such as the water, the natural gas, the sewerage system, the electricity and the telecommunications [1] contributes to a generalized increasing of the quality of life and is reflected in the organization and urbanizations of the population´s settlements. In consequence from the building compactness and continuity of the old city, raises a new type of fragmented and spread urbanism.

But, if for most of the infrastructures it is likely to "follow" the inhabited settlements based on municipals master plans, the classic approach of the telecommunications operator's is to focused their deployment plans on the urban administrative limits, where is forecast a guaranteed financial return.

In parallel, the growth of the telecommunications demand requires faster and wider broadband to each house/person leading towards a new global Information and Communication Technologies (ICT) era. The fact that the United Nations (UN) considered the telecommunications broadband access an universal right [2], has increased the pressure to expand the new generation telecommunication infrastructures, namely the high speed optical networks, to all type of municipal arrangements [3]. Nowadays, the main constrains for the deployment of those types of networks is not so much the technology maturity but the civil work´s inherent costs [4] mainly in rural and exurban scattered zones.

The research described in this paper is focusing in the exurban areas where the typical profile is people with higher college education level than closer-in suburbs, people that migrate to center city during the day for work, and return home at night, far from the crowd but with interest in being "*always on line*". A correct approach to the delimitation of the extended city and the urban dispersion borders can lead to a potential new planning area and profitable business plan, by integrating a set of methodological phases from the techno-economic analysis to the geographical modeling.

Considering this, the main objective of the paper is the evaluation of the overall costs when comparing different forms of habitat (concentrated and dispersed) at the local scale at a brownfield gigabit passive optical network (GPON).

This paper is divided as follows: Section I defines the context of the paper. Section II defines the technological scenarios´ of the study. It is dedicated to the description of the optical access network architecture and respective components' cost assumptions. Section III describes a method to extract a geographical model from real data of suburban settlements of typical Portuguese medium sized cities. Section IV presents the forecast results of a gigabit passive optical network, GPON network in both urban and suburban environments obtained by applying the extracted model at the local scale to a real city. Finally, a summary is presented.

II. INITIAL ASSUMPTIONS

In the telecommunication world there are several possibilities to reach each subscriber. They can be reached either individually at their mobile phones or at each one´s house by cable (in this paper, each house/door will be referred as Dwelling Unit, DU).

The access technology elected for this study was the GPON. The reasons that lead to the choice of an optical network as the high speed provider were the wider spread of the other most common solution, as described next and also the existence of ancient technologies that provide infrastructures that can be shared and consequently reducing the costs for the migration:

- Global access to the voice service is provided on the existence of the universal service (US) for plain old telephone service (POTS) and low debt internet based on Asymmetric Digital Subscriber Line (ADSL), [5-7];

- The broadcast television is also considered universal (e.g. more than 99.5% of the Portuguese population own at least one TV set [8] and 75% more than two);
- The mobile wireless subscriber penetration for both voice and data, in the context of the urban dispersion, can be considered not far from 100% (e.g. In Portugal reaches 120% [9]);

There is already in the field a fixed subterranean infrastructure that can be shared with other technologies and suppliers [10], assuming a share percentage of ducts around 50% and it is considered that most of the traditional urban and suburban areas already have a digital subscriber line (DSL) infra-structure and consequently at least one street cabinet or manhole already exists per neighborhood.

As the main focus in this work is the comparison of the local scale network, all the cost calculation will focus on the shared neighborhood infrastructure and all the access network´s segments shared among the several neighborhoods, such as the central office (CO), are excluded at this point. It is also assumed that 100% of the buildings, houses, schools and other institutions, under the limits of the urban dispersion occupation, will be equipped with optical fiber.

A. GPON Architecture at the Local Scale

Most logical architectures for the telecommunications networks are based around a system of three sets of layers. A common layer description is composed by: Core, Access and Client networks, see Figure 1.

The core network gives internetwork connectivity and interoperates with the "cloud" and other networks. The client network is the segment directly connected to the client through an electronic device depending of the technology such as a mobile phone, a TV set, a modem or a telephone, among others. The access network is the layer that connects both extremities segments and is the layer that is most often considered to the cost evaluation of a telecommunication´s network deployment, [11-13].

A fiber optical network based on a fiber to the home or building architecture (GPON FTTH/B) can be deployed in many different ways depending number of existing houses, the number of clients; the environment topology; streets rearrangement and equipment available or chosen by the engineer. In this particularly study, the network infrastructure is based on manholes, trenching ducts, or mast for aerial support of the fiber. This paper presents a redefinition of the standard concept, with a new vision of the access network infrastructure.

The local scale infrastructure: that is the part of the access network segment that is serving directly the neighborhood here referred as the base land unit, BLU. It excludes the Central Office. And the global access infrastructure is the network segment that is serving a wider territorial unit, as the whole city. It includes the core network and parts of the access networks that connects several neighborhoods or BLU´s, see Figure 1.

At this stage, it should point out the infrastructure costs of the global access infrastructure will be disregarded, not because they are irrelevant but due to the local scale perspective the global costs are equal in all cases. It is defined that all existing houses or public buildings are being deployed with fiber so the number of clients is equal to the number of existing "doors" or DU. It is also stated that each house receives 1 optical fiber.

Moreover, we also consider a fixed default architecture configuration so that the dispersion scenarios could be comparable. The FTTH/B GPON architecture chosen was based on the following considerations.

- In GPON, the maximum differential fiber distance is 20 km so the total dimension from the CO to the client cannot exceed 20Km [14];
- The optical link budget must safeguard a positive system margin ;
- It is expected that in average the length (L) of each fiber segment obeys the rule: L1<L2<L3 , see Figure 1;
- There is only one stage of passive optical splitters to distribute the fiber to each customer;
- The splitting ratio is fixed to 1:32 for all splitters;
- There can be more than one flexibility point (FP), depending of the neighborhood geometry.

B. Cost Analysis Method

The initial objective of this study is to obtain the cost comparison between several scenarios for the dispersive urban occupation, from the society point of view, as a whole. Any allocation or apportionment of costs between the telecommunication players will not be considered such as: service providers, infrastructure owners, state or subscribers. Likewise, the existence of taxes or any forms of payment mechanisms will also not be considered.

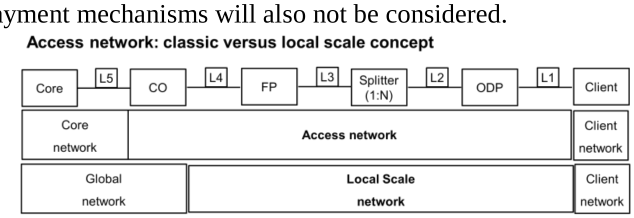

Figure 1. Telecommunication networks layers comparison with local scale concept.

The costs are reported in a reference period of 30 years. This option enables a cost / benefit analysis, since it seems reasonable with such time horizon to affect also the value of the buildings, in fact, from there on, the building requires maintenance work / reconstruction of very significant costs.

The cost of any infrastructure´s component or equipment (CT) is the sum of the Investment Cost (IC) and the Maintenance Costs (MC) in the fixed 30 year period (1).

$$CT\,(30years) = IC + MC \qquad (1)$$

For each component or equipment, the IC includes the civil works costs plus the acquisition and installation costs of the equipment. To calculate it, it is necessary to adopt a financial annual discount rate (FDR), that according to the

European Commission (EC) should be FDR=5%, [12]. IC can then be written for a 30 year period. It is taken into account for each component, the life time, V, and the need for its replacement.

The calculation of the number of investments for each component is given by K+1, where K is an artifice for non-multiple divisions and equals abs(the roundup of 30/V-1). The first parcel of (2) reflects the sum of the initial investments needed for a certain component, depending on its time life. Each year, the initial component cost (C_i) is affected by the FDR at the calculation year (n.V).

Sometimes, the component lifetime (V) can go beyond the 30 year assumed project life time, and because of that, in the second parcel of (2) is subtracted the portion of the investment corresponding to that differential, affected by the FDR at year 30.

$$IC = \left[\sum_{n=0}^{K} \frac{C_i}{(1+FDR)^{n \cdot V}}\right] - \left[\frac{(k+1)\cdot V-30}{V} \cdot \frac{C_i}{(1+FDR)^{30}}\right] = C_i \cdot f(V) \qquad (2)$$

Where Ci is the initial investment at year 0, V is the lifetime in years, K=abs (roundup (30/V-1; 0)) and FDR=0,05.

The maintenance costs are related to the energy consumption, periodical inspections and rents. It can be expressed based on the annual maintenance costs C_m and the FDR (5%), (3). Usually, this coefficient is described as a percentage of IC.

$$MC = \sum_{0}^{(V-1)} \frac{C_m}{(1+FDR)^n} = 16{,}14 \cdot C_m \qquad (3)$$

Where V is the lifetime in years, Cm are the maintenance costs that usually are described as a percentage of IC, %Cm and FDR=0,05.

C. GPON Investment and Expenses

The equipment prices are reported to the year 2010 and are based on data from the components suppliers found on the web. Whenever is possible the calculations are presented as a function of € per DU and if it is not possible is presented as € per meter. It is also assumed that 1 DU corresponds to 2.4 inhabitants, [15].

All the equipments and components are related to Figure 1.

1) *Fibers (fo):* The fiber segments are optical cables that contain several optical fibers (fo) namely groups of 288fo, 48fo or 24fo, can be buried in ducts or aerial supported on masts. In the case of buried fiber deployment, the value of civil works and ducts is assumed to be half the real price. This is due to the fact that it is assumed that at least 50% of the trenches already exist and are shared. In the case of the aerial deployment it is assumed that each mast height is around 8 m and the distance between masts is typically 50m.

If there is more than one flexibility point, FP, the L3 segment can be divided in smaller cable slots between FP´s, named L3.1 and L3.2 (from the client to the core). At L3.1 segment a 24fo cable is considered, and at L3.2 segment is assumed to have a 48fo cable. The final cable segment, L1, could be inexistent if the ODP is in the building façade. If the ODP is shared among several single houses L1 can be deployed either underground or aerial, unless the inter-house distance is economically impracticable, as will be discussed in Section IV.

Tables I and II presents the CAPEX and OPEX of the different fiber segments for the different types of deployment considered.

TABLE I FIBER COST BURIED DEPLOYMENT IN € AND PER METER

Fiber L3.2	**C_i**	**V**	**%C_m**	**f(V)**	**IC**	**MC**	**CT**
Civil work/m	25	50	2%	0,9	22.7	8.1	30.8
Equip.+ install.	2.3	20	4%	1.3	2.8	1.5	4.3
Total/m					25.5	9.6	35.1
Fiber L3.1/L2/L1	C_i	V	%C_m	f(V)	IC	MC	CT
Civil works/m	25	50	2%	0.91	22.7	8.1	30.8
Equip.+ Install.		20	4%	1.26	2.4	1.1	3.5
Total €/m					25.1	9.2	34.3

Where C_i is in €, V in years, C_m is a percentage of C_i, f(V) is a adimensional, IC, MC and CT are in €.

TABLE II - FIBER COST AERIAL DEPLOYMENT IN € AND PER METER

L3.2/L3.2/L2/L1	**C_i**	**V**	**%C_m**	**f(V)**	**IC**	**MC**	**CT**
(Mast+installation)/m	2.5	50	2%	0.9	2.4	0.8	3.2
Equipment and installation	3	20	4%	1.3	4.4	1.9	6.4
Total Cost/m					6.6	2.7	9.6

Where C_i is in €, Vin years, cm is a percentage of C_i, f(V) is a adimensional, IC, MC and CT are in €.

2) *Flexibility points (FP):*

The flexibility points, usually in manholes, are used to separate physically the cable in the hub corners and street cross points. They are define as 1:N type, depending on the number of cables they aggregate in one cable. In this study, FP1 is type 1:2 that means that receives 2 L3.1. cable segments from the splitters and join them into 1 cable of 48fo (L3.2). Then in 1:6 type, FP2, the process repeats and FP2 ends with 6*48=288cable (L4) of 48fo entering the CO.

Table III shows the cost of the equipment and man work for the most common installation at underground cable camber (manhole) for a 30 year analysis period.

TABLE III - FLEXIBILITY POINT COSTS PER EQUIPMENT IN €

	C_i	**V**	**%C_m**	**f(V)**	**IC**	**MC**	**CT**
Civil works	360	50	2%	0.91	328	116	444
Equip.+instal	438	30	15%	1	438	1060	1498
Total €/unit					766	1176	1942

Where C_i is in €, V in years, C_m is a percentage of C_i, f(V) is a adimensional, IC, MC and CT are in €.

3) *Splitters:* The splitters are power dividers usually mounted in Fiber distribution Hubs (FDH) cabinet's also known as street cabinets. The theoretical scenario of a fully occupied street cabinet with maximum capacity of 24

splitters was assumed. From the central office and after the flexibility points, each 1:32 type splitter receives a 24fo cable and divide each fiber in 32 fibers grouped in cables of 24fo. In this scenario, each splitter was able to serve 788 DU´s, if all the fibers were used for clients, however a percentage is reserved to network maintaince.

Table IV shows the cost of each cabinet with the 24 splitter stage for a 30 year analysis period.

TABLE IV - STREET CABINET WITH 24 SPLITTERS COSTS IN €

	C_i	V	$\%C_m$	f(V)	IC	MC	CT
Cabinet and installation	2820	20	4%	1.26	3557	1821	5377
Equipment and installation	8759	15	15%	1.28	12963	21205	34168
Total Cost per cabinet of 24 splitters					16520	23025	39545

Where C_i is in €, Vin years, cm is a percentage of C_i, f(V) is a adimensional, IC, MC and CT are in €.

4) Optical Distribution Point (ODP): The ODP Box is an infrastructure component which main function is to connect the distribution network to the client and it may be mounted either indoor or outdoor. Each ODP receives a 24fo cable. In this study, it is assumed that there are no splitters inside the ODP and 4 of the 24 fibers are reserved for the telecommunications operator's maintenance issues. Each ODP is shared among an integer number of buildings or houses up to a certain inter-house distance. Table V shows the cost of each ODP at each building entrance for a 30 year analysis period.

TABLE V – OPTICAL DISTRIBUTION POINT COST IN EUROS

	C_i	V	$\%C_m$	f(V)	IC	MC	CT
Equipment and installation	120	20	15%	1.26	151	291	442
Total cost/ODP					151	291	442

Where Ci is in €, V in years, Cm is a percentage of Ci, f(V) is a adimensional, IC, MC and CT are in €.

The following table, Table VI illustrates the multiplication factor of each component relative to the number of dwelling units served.

TABLE VI - GPON COMPONENTS MULTIPLICATIVE FACTOR

Network element	Factor	Min. use	Low use	Max. use
FP1	6	384	3840	7680
FP2	2	64	640	1280
Splitter	32	32	320	640
ODP	1 to 20	1	10	20

III. URBAN DISPERSION IDENTIFICATION METHODOLOGY

The study of urban dispersion on a local scale requires the adoption of operational concepts. This research uses the notion of "Base Land Unit" (BLU), which represents a piece of land for experimental studies [16], which will be used to characterize the land occupation by defining a BLU ranking. The recognition of BLU is more difficult in urban territories because its fragmentary and dispersive expansion dynamics are not consistent with the administrative limits.

The research project's case studies are two typical medium European types of cities. One type which is generally regarded as a concentrated city that developed (more or less) homogeneously around a nuclear old city and another type that derived from the same type of origin but for several factor grew in such a way that is usually associated to a more dispersed or diffused territory.

A. Local Scale BLU Modeling

The first approach of the land unit, LU characterization consists on the analysis of digital aerial photos to delimit the borders of the extended city, based on the maximum distances between buildings. This digital method typifies the building agglomeration in three types: continuous, dispersed and rarefied.

The Base Land Unit, BLU, concept integrates and almost coincides with other well-known territorial units, namely the neighborhood in its everyday meaning. The BLU concept differs from the neighborhood as it does not necessarily refer to an exclusively residential area – it may also encompass central or industrial areas, techno-centers, a dispersed settlement area or even an agricultural and/or forested area within the extended city.

In this study, with the focus on the local scale, a base land unit for the concentrated occupation with no more than 3000 residents and corresponding to 1200 DU´s is considered. The DU's are most of them buildings but also single houses; it also includes some green plazas and the existence of public equipments as schools, commercial zones and hospitals in a total of 133 DU´s.

The geographic applied method identified attributes to differentiate standard BLU´s scenarios to work with, [17] as building aggregation in city blocks or one-to-one; usage as uni/bi-functional versus multi-functional buildings and distance to the public equipments and commerce, among others.

The observation and quantification of these attributes lead to a classification of the Concentrate BLU in two main groups: Classic and Modernist, with each one of these classifications further divided in uni/bi-functional or multi-functional building aggregation leading to 4 types of scenarios [16]. The dispersed urbanization characterization is followed by several defined attributes that combined can formulate 9 different types of scenarios [17]. Only the three most suitable were chosen to the reality in study. These environments are characterized by groups of edifications as: linear and continuous (LC), scatter and occasional (SO) and uniform and occasional (UO).

As an example, Figure 3 illustrates the final aspect of the base land unit, concentrated classic and dispersed uniform and occasional based on the previous attributes manipulation. For the dispersed BLU occupation, it was defined an universe of 1000 inhabitants corresponding to 400 DU´s. For this type, of BLU specific taxonomy and adapted attributes were tested. The attributes adopted include the linear density (LD) indicator which can be expressed by the number of houses per linear track. Its results were compared with the real environment and as a consequence a LD grade scale was defined. One of the conclusions of this indicator´s reading is that is also applicable to all type of BLUs and not only to the dispersion ones.

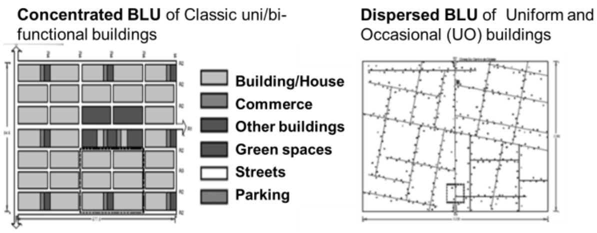

Figure 2. Sprawl scenarios: concentrated BLU of Classic uni/bi-functional buildings, on the left and Dispersed BLU-UO, on the right.

Table VII presents the summary of the main characteristics of the chosen standard scenarios.

TABLE VII - BLU STANDARD SCENARIOS

	Concentrated BLU				Dispersed BLU		
	Uni/bi-functional		Multi-functional		LC	SO	UO
	Classic	Modern	Classic	Modern			
Pop.	3000				1000		
Area (ha)	29.4	54.5	24.6	18.2	375	375	800
Building	828	1234	202	88	400		
LD (#DU/m)	19.2	10.4	28.5	40.8	7.5	5.3	1.5

Where BLU stands for Base Land Unit, LC stands for Linear and Continuous urbanizations, SO stands for Scatter and Occasional urbanizations and UO stands for Uniform and Occasional urbanizations. The area is in hectare (ha) and the Linear Dispersion (LD) is the number of DU per 100 meters of street.

IV. RESULTS

At this point, all the data presented in the previous sections is compiled. The telecommunication network´s technology and architecture were chosen; several components of a local scale optical fiber network were identified, as well their cost in a 30 years period and the urban+suburban distribution was characterized leading to two types of urban settlements: the concentrated and the disperse with several variants.

This section resumes the conclusions after applying the described techno-economic method to the geographical model and respective scenarios.

A. Architecture tips: profitable distance to share ODPs

The deployment of the optical network in all seven urban scenarios, Table VII, followed the same method. First, all the ODP were placed as close as possible to the buildings, in order to capitalize its cost in a relation with 1 ODP per 20 DU´s. The ODP´s have an output of 24 fibers, but it was assumed that 4 fibers were reserved to operator´s maintenance operations. If the scenario is not a building but several individual houses the same ODP is shared among them as long they are in the same side of the street.

At this point it is interesting to understand how long L1 can be, before the need of a second ODP considering the balance of the investment in fiber and in another ODP. The depicted variables R1 and R2 try to illustrate this theoretical situation. On the left of the image, it is shown the ideal situation of 1 ODP per building, in the middle there is the case of an ODP sharing using underground fiber and in the right there is the situation of an ODP sharing with aerial fiber, see Figure 3.

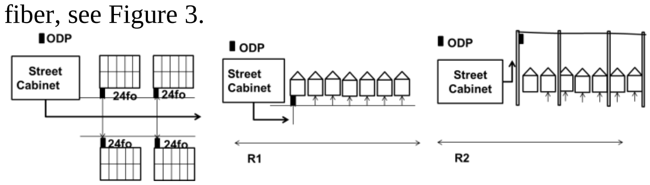

Figure 3. Testing scenarios for techno-analysis of ODP sharing: the ideal situation of 1 ODP per building (on the left), the ODP sharing with fiber underground (in the middle), ODP sharing with aerial fiber (on the right).

In a concentrated environment and according to the pattern adopted, 1 FP serves 12 cabinets and each one serves 32 ODP and the cost evaluation of the Local Scale Cost per ODP (LSCO) can be calculated as presented in (4).

$$LSCO = \frac{Cost\ FP1 + Cost\ FP2}{n^{o}\ of\ served\ ODP_1} + \frac{Cost\ per\ full\ cabinet}{n^{o}\ of\ served\ ODP_2} + ODP\ cost \qquad (4)$$

Within this perspective a first finding is that R1=49m and R2=176m is the maximum recommended L1, see Figure 1 before use another ODP. After the distribution of the ODP´s, it is necessary to place the cabinets with the splitters optimizing the L2 (it also depends on licenses and municipally authorization). And depending on it, the location for the flexibility points should be placed optimizing L3 length.

B. GPON Cost comparison per geographic model

Taking these rules into attention and deploy the chosen GPON architecture per geographic scenario it is possible to apply the developed calculation algorithm based on MSExcell to each one of the urban concentrated and dispersed settlements. A shopping list can be extracted from the calculation tool and can be seen in more detail in TABLE VIII.

As expected, the investment in infrastructure is always bigger in dispersed than in concentrated enviroment but massive saving can be done either by sharing or choose aerial deployment. This last solution is less expensive from 58% to 78% than the buried one, for 50% of ducts shared and can reach more than 85% in dispersed uniform and occasional settlements if there is a 100% sharing.

V. CONCLUSIONS

The deployment of broadband networks is one of the target measures of several governments and entities in many countries around the world. In some geographic areas, it can be interpreted as an answer to the market demand for new and attractive high speed applications; in other areas it is seen as a seed of development. One relevant fact is that this dichotomy is shared among many countries, ranging from the most industrialized to the emerging economies, meaning that in most of the countries both situations can be found. In fact, there is a widespread understanding that the access to broadband is a factor of society's equitable opportunities. However, the cost is still a drawback and investments should be done wisely.

This paper presented the quantification of a PON network using an approach that combines fiber optics engineering and deployment with geographic tools. This analysis was focused at the local neighborhood level, taking into consideration urban and exurban scenarios modeled by the geographical method.

This analysis is part of a project made with several departments, to identify the costs of all type of infra-structures as a function of the degree of urban dispersion (telecommunications, gas, water, sewage, garbage collection, electricity and public lightning) based on the characterization of two Portuguese medium sized cities. The main objective of the global project is to attribute a cost value per DU in a modern city and surroundings as a guideline to future concerted territorial planning policy.

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TABLE VIII– COST ELEMENTS FOR PASSIVE OPTICAL NETWORK STANDARD BASE LAND UNIT SCENARIOS WITH 50% DUCT SHARING

50%duct sharing	**Concentrated BLU**				**Dispersed BLU**					
Usage	**Uni/bi-functional**		**Multi-functional**		**Linear and Continuous**		**Scatter and Occasional**		**Uniform and Occasional**	
Scenarios	**Classic**	**Modernist**	**Classic**	**Modernist**	**Under.**	**Aerial**	**Under.**	**Aerial**	**Under.**	**Aerial**
#ODP	92	66	72	92	23		27		23	
#Cabinets (24 splitters)	3	2	3	3	1		3		4	
#FP	2	2	2	2	2		2		2	
L1 (*m*)	5402	20844	3120	0	12654	33856	13938	35800	54996	64400
L2 (*m*)	5043	4536	3645	3572	4367		3651		10535	
L3.1 (*m*)	384	369	267	143	236		290		150	
L3.2 (*m*)	365	360	542	326	50		3755		1855	
Cost (€ /DU)	450€	890€	330€	230€	1700€	920€	2250€	1030€	6700€	1990€
% Civil works	63%	80%	57%	42%	70%	90%	68%	90%	75%	90%
%Equipment	37%	20%	43%	58%	30%	10%	32%	10%	25%	10%

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