

DESIGN AND CONSTRUCTION OF **OPTICAL LINES** IN A MODERN CITY UNDER HIGH-DENSITY DEVELOPMENT:

TECHNOLOGICAL IMPERATIVES,
ECONOMIC EFFICIENCY, AND
PRESERVATION OF
ARCHITECTURAL HERITAGE

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Design and Construction of Optical Lines in a Modern City under High-Density Development: Technological Imperatives, Economic Efficiency, and Preservation of Architectural Heritage

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Abstract. The present study provides an expanded techno-economic analysis of designing and constructing fiber-optic communication lines in a high-density urban environment typical of recent megacities. Against the backdrop of accelerated network-traffic growth driven by the scaling of generative artificial intelligence, the proliferation of ultra-high-definition video streams (8K/VR), and the development of fifth- and sixth-generation networks (5G/6G), last-mile infrastructure increasingly functions as a binding constraint for the digital economy. The central hypothesis substantiates the position that the traditional civil-construction approach—open-trench installation—has exhausted its potential for economic and logistical effectiveness within historically established territories. The argumentation leads to the conclusion that a transition is required toward a hybrid model combining micro-trenching technologies, non-destructive testing and verification of underground utilities (GPR/SUE), and intelligent practices for reusing existing municipal infrastructure. Particular emphasis is placed on comparing network deployment in legacy housing stock versus new construction, revealing a systemic disparity in CAPEX structure and the profile of operational risks. Based on a critical review of more than thirty authoritative sources, including materials from Deloitte, IEEE, the Fiber Broadband Association, and Cartesian for 2024, a decision matrix for selecting an installation method is developed. In addition, algorithmic models are presented for evaluating network reliability and total cost of ownership, together with program code intended to visualize key economic indicators.

Keywords: fiber-optic communication lines, high-density urban development, micro-trenching, nano-trenching, open trench, FTTH, XGS-PON, 50G-PON, ODN, GPR, SUE, CAPEX, TCO, reliability, Brownfield, Greenfield, architectural heritage.

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INTRODUCTION

The contemporary urban environment is being rapidly redefined by digitalization processes: whereas in the industrial era the city’s system-forming “arteries” were considered to be transport corridors and energy networks, by 2025 a comparable role has begun to be performed by fiber-optic infrastructure, which provides (i.e., provides) connectivity, computational accessibility, and service resilience. According to the International Telecommunication Union (ITU), the global number of Internet users reached 5.5 billion; however, a pronounced asymmetry of availability persists both between urban and rural territories and within megacities themselves—between modern business clusters and the historic center [1]. In this context, the telecommunications sector—whose 2024 volume is estimated at USD 1.53 trillion—faces a structural contradiction: demand for throughput is rising at an accelerated pace (in the United States, households already consume an average of 600–800 GB of data per month), while the spread of AI services shifts requirements toward minimizing latency to single-digit milliseconds [2]. At the same time, physical realization of these requirements within the urban fabric is constrained by the saturation of subsurface space with utilities, strict regimes for protecting cultural-heritage assets, and the high cost of earthworks, rendering traditional construction practices progressively less effective [3].

The scientific and applied relevance of the problem is determined by the need to conceptually resolve the conflict between the technological inevitability of ubiquitous deployment of next-generation FTTH networks (XGS-PON, 50G-PON) and the inertia of civil construction relying on the open-trench method. In 2024, the median cost of underground fiber installation in the United States reached USD 18.25 per foot, directly worsening project economics and, in some cases, calling payback into question—especially in areas of established development. The critical divergence between deployment conditions in new

districts and historically formed neighborhoods produces a dichotomy of design approaches. Greenfield scenarios create an effectively “clean” baseline environment, enabling placement of duct banks at an early construction stage, application of microduct systems, and rationalization of network topology; the principal uncertainty, however, shifts into the domain of early capital outlays and the accuracy of forecasting future demand [4 5]. By contrast, Brownfield is characterized by extreme engineering complexity: typical constraints include a deficit of reliable documentation on existing utilities, limited feasibility of heavy equipment, prohibitions against interventions affecting historic-building façades, and requirements to execute works without halting urban life. In older multi-dwelling stock (MDU) formed prior to the 1980s, vertical cable risers are often absent, forcing a shift toward individualized retrofit schemes with high unit costs and elevated implementation risks [6].

Purpose of the study: to substantiate and formalize an engineering-economic selection of technologies for designing and constructing urban fiber-optic lines under dense and historic development, demonstrating the advantage of a hybrid model (micro-trenching + GPR/SUE + infrastructure reuse) over open-trench installation amid rising FTTH/5G/6G requirements and traffic growth.

The scientific novelty of the research framework is established through the development of an adaptive micro-invasive construction concept, in which installation methods (micro-trenching, nano-trenching) are classified by pavement type and climatic zone, grounded in material-durability data obtained during field trials in 2023–2024 [7]. In addition, a comparative reliability model for aerial versus underground lines is proposed in the context of climate change, based on failure-rate statistics per 1,000 km of line per year, and an algorithmic approach to retrofitting historic buildings is formulated that minimizes structural intervention by applying optically transparent cables and leveraging existing architectural voids.

The author’s hypothesis is that integrating micro-trenching technologies

in combination with AI-based predictive modeling and ground-penetrating radar (GPR) scanning can reduce the economic gap between project execution in Greenfield and Brownfield, decreasing total cost of ownership (TCO) in historic centers by 30–40% while maintaining reliability at a level comparable to traditional deep-burial installation.

CHAPTER 1. EVOLUTION OF URBAN OPTICAL-NETWORK ARCHITECTURE AND STANDARDS

Chapter 1 examines the evolution of the architecture and standards of urban optical networks in 2024–2025 in the context of the transition from gigabit access to multi-gigabit profiles. The analysis substantiates the exhaustion of GPON scalability and the expected migration to XGS-PON and, subsequently, to 50G-PON, while emphasizing that modernization affects not only the active segment (OLT/ONT) but the entire ODN infrastructure (routes, closures, splitters, cross-connects, and in-building distribution). This shift increases sensitivity to optical-budget constraints, connection quality, and nonlinear/installation losses. The chapter also highlights the role of bend-insensitive fibers of the G.657 classes—minimum bend radii, micro-damage behavior, and interface contamination—and the tightening requirements for monitoring and diagnostics (OTDR and fiber inventorying) needed to preserve reliability as fiber density increases and routing becomes more complex [8, 9].

The chapter further addresses FMC convergence, in which a single urban fiber plant simultaneously serves FTTH and 5G xHaul contours under ultra-dense network (UDN) conditions and high small-cell density, raising requirements for capacity, redundancy, and rapid switching. A mathematical apparatus for long-horizon (15–20 year) capacity estimation is then introduced based on queuing models, demonstrating how “heavy” services (8K, VR) reshape design trade-offs (split ratio, reach, allowable loss, receiver sensitivity). The discussion extends to coexistence scenarios for multiple PON generations within a single ODN (GPON/XGS-PON/50G-PON via wavelength plans) and to the need for more granular planning and instrumented verification of passive-line quality during large-scale migration.

1.1. Technological Transition to Multi-Gigabit Speeds

The architecture of urban networks in 2024–2025 is increasingly shaped by the transition from gigabit access to multi-gigabit service profiles, driven by exponential growth in consumption of high-bitrate services and reduced application tolerance to latency and latency variation. The GPON standard, which served as the de facto foundation of mass optical access over the last decade, is approaching scaling limits in throughput and subscriber density while preserving quality-of-service requirements. Accordingly, a predictable drift is observed toward XGS-PON with symmetric 10 Gbit/s speed and to the next technological cycle—50G-PON—anchored in ITU-T Recommendations of the G.9804 family and ratified during 2021–2023 [9].

For high-density urban development, this transition implies modernization not only of the active segment (OLT/ONT) but also of the optical distribution network (ODN) as an integrated set of routes, closures, splitters, cross-connects, and in-building cabling. In practical terms, deployment of 50G-PON increases network sensitivity to the aggregate optical power budget and to nonlinear losses, and it also makes localized degradation factors associated with installation mechanics more critical. Reduced macro-bend losses become a technological constraint in constrained risers and legacy buildings, where minimal bend radii and dense cable packing are essentially unavoidable; therefore, the role of fibers compliant with G.657.A2/B3 requirements—exhibiting enhanced bend performance and predictable characteristics under complex route geometry—becomes more prominent [10].

In parallel, urban fiber undergoes a functional transformation: it ceases to be merely a fixed-access medium and acquires the attributes of a universal transport layer for heterogeneous domains. The convergent FMC (Fixed-Mobile Convergence) model implies operating a unified fiber infrastructure both for FTTH and for xHaul tasks in 5G networks, including fronthaul/midhaul/backhaul depending on the selected radio-access architecture. Under ultra-dense network (UDN) conditions—where the density of small-cell placement in central districts

may reach hundreds of nodes per square kilometer—the need for high fiber capacity in cable systems grows, distribution topology becomes more complex, and requirements for redundancy and fast switching become comparable to carrier-grade transport networks [11].

Technical feasibility of multi-speed access in urban environments largely relies on coexistence scenarios for PON generations within a single physical ODN, including parallel operation of GPON/XGS-PON/50G-PON on different wavelengths and phased migration of the subscriber base. However, higher speeds amplify the importance of design trade-offs among split ratio, reach, allowable loss, and transceiver sensitivity requirements; as a result, traditional “universal” splitting schemes often give way to more targeted planning: allocating dedicated branches for heavily loaded clusters, applying cascaded splitting structures only under strict budget control, and imposing tighter regulations on connectorization quality and fusion-splice workmanship [9].

An additional factor is operational resilience: increasing fiber density and route complexity raise the risk of parameter degradation due to micro-damage, contamination of optical interfaces, and process errors during mass activations. Under these conditions, the role of monitoring and diagnostics systems strengthens (including reflectometry and centralized fiber-inventory management), as do standardized installation procedures and disciplined bend management along the entire path—from trunk segments to in-building sections. The combination of bend-insensitive fibers, a correctly calculated optical budget, and instrumentally verified ODN quality provides the necessary foundation for scalable deployment of XGS-PON and 50G-PON in the urban environment without degrading reliability and service-availability indicators [10].

1.2. Mathematical Modeling of Throughput

When designing modern fiber-optic communication lines, it is critically important to account not only for current needs but also for a throughput reserve

over a 15–20-year horizon. Network-capacity calculation should be grounded in queueing (mass-service) models.

Under 2024 conditions—when 8K streaming requires 100+ Mbit/s of bandwidth and VR applications are latency-sensitive—designers are forced to reduce split ratios in dense districts to 1:32 or even 1:16, increasing the number of required fibers in the feeder/trunk plant [9].

Below is Figure 1 showing the dynamics of growth in network bandwidth requirements depending on the year and access technology.

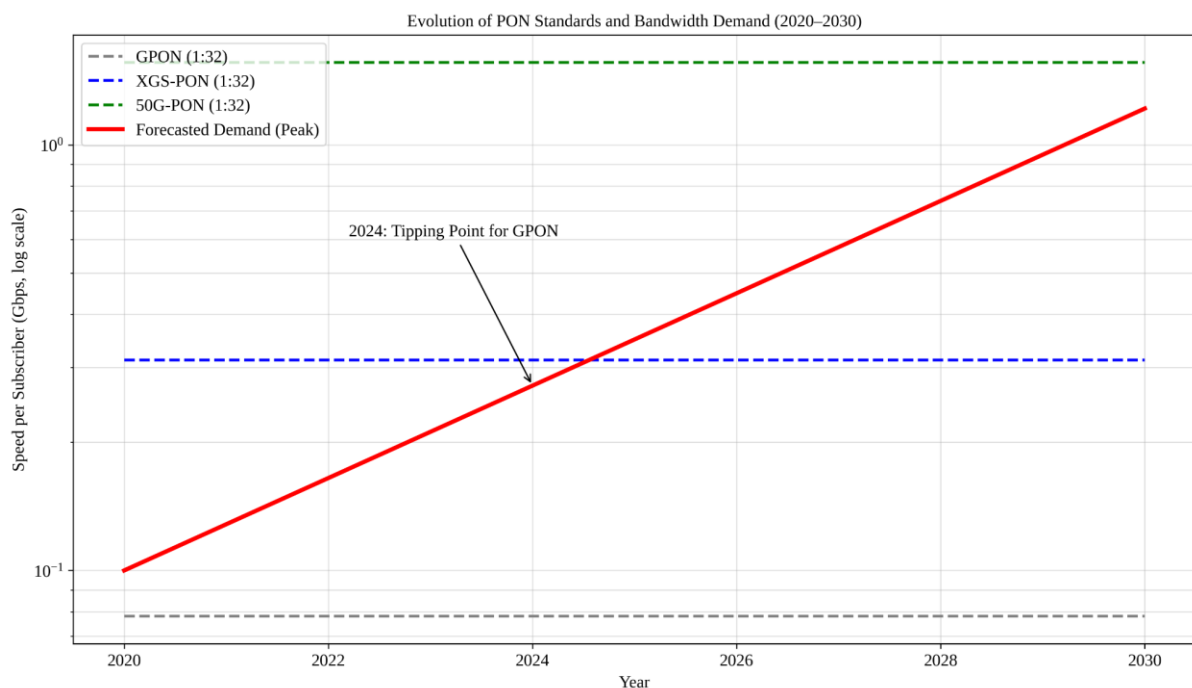


Fig. 1. Forecast of Traffic Consumption (compiled by the author based on [9]).

The chart analysis indicates that by 2024–2025 the capabilities of “classic” GPON under conditions of dense development and intensive content consumption become exhausted, necessitating mass migration to XGS-PON. This transition entails replacement of active equipment and verification of passive-line quality (OTDR testing, attenuation assessment).

CHAPTER 2. TECHNOLOGICAL CONSTRUCTION METHODS IN THE URBAN ENVIRONMENT

Selecting a construction method in high-density urban development is invariably a compromise among cost, speed, reliability, and administrative constraints. In 2024, the range of available technologies expanded markedly, offering practical alternatives to traditional excavation.

2.1. Micro-Trenching: An In-Depth Analysis

In recent years, micro-trenching has become established as a technologically and organizationally preferable method for deploying fiber-optic infrastructure in urbanized territories with rigid pavement structures. The method is based on forming a narrow saw cut in the pavement structure with a width on the order of 1.5–5 cm and a depth sufficient to place microducts, while typically not reaching the structural base of the roadway (commonly 20–30 cm) [12]. This geometry of intervention fundamentally reduces the volume of pavement destruction and localizes work within a minimal corridor, which is particularly significant under conditions of high traffic intensity and stringent noise- and dust-emission constraints.

From a practical standpoint, the effectiveness of micro-trenching is determined by the high productivity of specialized units using diamond cutting blades (diamond-based micro-trenching). With proper organization of the work front, production rates on the order of 300–500 m per shift are achievable, which is multiple times higher than classic excavator-based technologies; in certain scenarios, values around 1,500 feet (≈ 450 m) per day are reported [14], [13]. Acceleration

of construction yields not only direct savings in labor time but also a reduction in indirect losses associated with constrained transport accessibility and elongated approval timelines.

The economic effect manifests primarily through reduced direct costs for earthworks and reinstatement operations: lower volumes of removed material, reduced hauling logistics, and minimized backfill and pavement-restoration expenditures may decrease construction cost to approximately 60% of the open-trench method [15]. An additional advantage is reduced disruption to traffic flows: when fast-curing compounds are used to seal the cut, roadway reopening can occur within short timeframes, lowering socio-economic externalities and simplifying compliance with municipal restrictions.

At the level of engineering risk, a key vulnerability of micro-trenching is the potential impact on pavement durability and the mechanical/climatic sensitivity of the seam zone, including the protection of the installed cable path. In cold climatic regions, cyclic freezing and thawing may cause vertical heaving of the trench fill (frost-heave effect), which has been documented in observations including cases in Canada (Edmonton) [7]. In current practice, risk mitigation is achieved through selection of elastomeric polymer compounds with improved crack resistance and deformation tolerance, as well as constructive anchoring solutions for microducts that reduce the probability of displacement and stress concentration within the cut zone.

The role of technological discipline also increases when selecting the route alignment and the cut location relative to pavement-structure elements. Municipal regulations in a number of major cities (including San Francisco and Los Angeles) specify a preferred placement of the micro-trench in the joint zone between asphalt and the concrete gutter pan, which reduces wheel-load effects and lowers the likelihood of accelerated seam deterioration [17]. In this way,

micro-trenching effectively moves from the category of a “fast installation method” into the domain of a standardized technology in which outcome quality is determined not only by cutting speed but also by correct localization of the intervention within the pavement structure.

From an engineering and operational perspective, solution stability critically depends on controlling the geometry and condition of the cut: consistent width and depth, absence of undercuts and microcracking in the adjacent pavement mass, and cleanliness of the channel prior to compound placement directly affect adhesion and seam watertightness. A set of measures—including instrumental verification of cutting parameters, regulated surface preparation, and use of compounds with predictable rheology—reduces the probability of moisture infiltration and subsequent frost damage, which is particularly important for the long-term reliability of the urban ODN.

In urban-planning and managerial terms, micro-trenching creates prerequisites for more flexible capital-works planning: reduced impact zones facilitate coordination with owners of underground utilities and increase compatibility with the “minimally invasive” street-reconstruction concept. At the same time, the effectiveness of scaling the method in a city environment relies on unifying design decisions (microduct type, protective entry schemes, seam requirements) and on forming reliable as-built documentation that ensures subsequent traceability and safe execution of repair works without secondary damage to cable infrastructure.

2.2. Traditional Underground Installation vs. Aerial Lines: 2024 Statistics

Despite active deployment of new technological solutions, classical approaches to constructing fiber-optic infrastructure retain a high share of practical use. According to the Fiber Broadband Association’s reporting, the cost of traditional underground installation shows a persistent upward trend and

reaches a median level of USD 18.25 per foot; under unfavorable engineering-geological and urban-planning conditions (rocky soils, high density of crossings with active utilities), values may increase to USD 50 per foot. This variability reflects not only differences in soil mechanics and route accessibility but also cumulative costs for permitting, utility relocations, temporary traffic-management schemes, and reinstatement of disturbed urban improvements [18].

For aerial installation, the median cost remains substantially lower, at approximately USD 6.55 per foot. However, in high-density urban development, applicability is often limited by the absence of poles (conversion of overhead utilities to underground), visual-environment requirements (“clean sky”), and increased operational vulnerability. Based on Bellcore and AFL materials, aerial lines exhibit failure frequencies exceeding underground-route indicators by a factor of 25, which is attributed to wind loading, icing, tree falls, and road-traffic incidents [18]. As a result, direct CAPEX advantages of aerial placement are frequently offset by higher outage risks, costs of emergency restoration, and stricter redundancy requirements [20, 22].

An additional contribution to construction-method selection is made by the engineering specificity of “accelerated” underground deployment technologies—micro-trenching, horizontal directional drilling, and pulling through existing duct systems. When correctly matched to route conditions, such solutions can reduce excavation volumes and compress schedules; however, their economic efficiency depends materially on the availability of spare duct capacity, infrastructure-owner regulations, permissible bend radii, and the risk of intersecting unrecorded utilities. In practical planning, this results in the need for probabilistic assessment of unforeseen work and allocation of contingencies for surveys, instrumental tracing, and pavement reinstatement—especially critical for historic centers and zones with highly saturated underground networks (see table 1).

Table 1. Comparative Analysis of Installation Methods (2024 Data) (compiled by the author based on [14-19]).

Parameter	Traditional Underground (Open Trench)	Micro-Trenching (Micro-trenching)	Aerial
Cost (USD/ft)	USD 18.25 (median)	~USD 10.00–15.00	USD 6.55 (median)
Speed (m/day)	30–50 m	300–500 m	>1,000 m (when poles are available)
Reliability (failures)	Low (0.085 failures/1,000 km/year)	Medium (roadwork-related risk)	High (2.13 failures/1,000 km/year)
Labor intensity	High (≈80% of costs—labor)	Low	Medium (make-ready work)
Environmental footprint	High carbon footprint	Low (limited waste)	Low

From a methodological standpoint, comparing options is best performed not only by cost per foot but also by integrated life-cycle cost (TCO), incorporating reliability, maintainability, serviceability, and the consequences of failures for service quality. Underground solutions generally outperform in resilience to climatic and technogenic impacts, whereas aerial lines provide faster commissioning and flexibility for expansion but require intensified risk management and operational governance. Under current conditions, priority shifts toward a systemic balance among CAPEX, damage probability, restoration time, and urban-environment requirements, since these parameters ultimately determine operational predictability and the network’s economic efficiency.

2.3. Ground-Penetrating Radar (GPR) and Accident Prevention

Under conditions of dense urban development, a key source of financial losses and safety threats is the probability of damaging active underground networks—gas distribution, water supply, power systems, and other utilities. Incidents involving exposure and unintended disruption of routes during earthworks account for the largest share of operational failures in cable infrastructure; excavation-related damage is responsible for approximately 60% of cable-line incidents [19]. Such events generate not only direct restoration costs but also cascading consequences—from forced outages and penalties to socially significant risks associated with disruption of critical urban systems.

To reduce uncertainty and move from reactive consequence handling to preventive risk management, standardized approaches to subsurface utility engineering are applied. Contemporary SUE (Subsurface Utility Engineering) practices call for mandatory use of non-destructive methods for identifying and refining utility locations prior to construction operations [21]. The most common instrument in this framework is ground-penetrating radar (GPR), enabling formation of a three-dimensional representation of the subsurface environment with detection of both metallic and non-metallic objects, including PVC and ceramic pipelines [21].

Applied evidence indicates that multi-frequency GPR systems operating in the approximate 250–700 MHz band can improve positioning reliability for engineering objects at depths up to 2–3 meters even in heterogeneous urban soils and under high interference saturation [21]. This frequency configuration supports a workable balance between spatial resolution and signal penetration depth, which is especially important in the presence of multilayer pavement structures, technogenic fills, and locally overmoist zones typical of the urban environment.

A substantial effect is achieved when moving from fragmented survey outputs to their engineering interpretation within a unified digital project

environment. Integrating GPR-derived point clouds and utility traces into BIM models enables alignment of design solutions with the actual underground situation, allowing micro-trench routing with high spatial accuracy and minimizing clashes. In this mode, routing becomes not merely a geometric task but a constraint-management procedure in which permissible clearances to utilities, tolerance limits for deviations, and substantiation of solutions for permitting stakeholders are critical.

At the same time, engineering reliability of results is determined by the correctness of the field protocol and verification procedures: equipment calibration, accounting for soil dielectric properties, repeated passes along key segments, and quality control of interpretation. In practice, combining GPR with point-based confirmatory methods (e.g., vacuum excavation at control points) enables upgrading detected objects to higher confidence levels and forming as-built data suitable for subsequent operations. As a result, the probability of costly work stoppages decreases, schedule predictability improves, and the overall level of industrial safety rises during construction and modernization of cable routes.

CHAPTER 3. INSTALLATION SPECIFICS: LEGACY HOUSING STOCK (BROWNFIELD) VS. NEW DEVELOPMENTS (GREENFIELD)

This chapter integrates practical experience and client-provided materials, demonstrating fundamental differences in project-delivery approaches.

3.1. Brownfield: Challenges of Historic and Older Development

Work in legacy housing stock—buildings erected before the 1980s, as well as properties within historic districts—falls simultaneously into the category of engineering-intensive and administratively sensitive projects. Unlike contemporary office and residential complexes, such structures were generally not designed to accommodate structured cabling systems and typically lack spare capacity within cable pathways. As a result, fiber deployment becomes a task in which design is tightly coupled with assessment of the as-is condition of building structures, existing utility networks, and legal constraints governing any intervention in the fabric of the property.

The most frequent problem is the absence of viable routes or their functional unsuitability: vertical risers are often congested with legacy copper wiring, coaxial lines, and unstructured ad-hoc placements, or they may be entirely absent. This forces the search for alternative pathways—through ventilation ducts, elevator shafts, or along façades—yet many such solutions are constrained by fire-safety requirements and evacuation-route regulations [23, 25]. Architectural and heritage-protection constraints add a further layer of complexity: for listed buildings, the principle of “reversibility” is commonly applied, under which drilling, chasing, and openly installed trunking may be prohibited or permitted only in strictly limited scope. Practical implementation in such cases tends to rely on specialized variants—surface trunking selected and painted to match finishes, concealed routing behind baseboards, and “invisible fiber” technologies, typically realized as transparent microfilament fixed to

surfaces using adhesive methods [24].

The economics of connecting such properties also differs fundamentally from that of new builds. The cost of retrofitting a single unit in a historic building may fall within the range of £2,000–£10,000, whereas in modern projects the unit cost is typically an order of magnitude lower [26]. This premium is driven by a high share of manual operations, the need to restore finishes and interior elements, and complex approval procedures together with the formalization of access rights (wayleaves) under conditions of multiple owners and heterogeneous occupancy status [26]. An additional risk cluster is formed by technical and sanitary-hygienic factors: the presence of asbestos and lead-based paints requires specific protective measures for personnel and regulated work procedures, affecting both schedule and budget. Moreover, thick masonry walls and complex floor plans degrade radio propagation, making it economically and technically justified to extend fiber not merely to an entry zone but deeper into premises (FTTR) to ensure stable access parameters [6].

Under these conditions, design is best shifted toward an “inspection—model—installation” workflow, in which initial solutions are refined based on a detailed inventory of routes, materials, and constraints on intervention. An effective practice is the early creation of a map of permissible installation zones, linked both to protected elements (stucco, historic panels, decorative finishes) and to fire-protection regimes, thereby excluding routes that are clearly unacceptable already at the concept stage. This approach reduces the probability of rework, minimizes conflict with supervisory requirements, and increases budget predictability while preserving the integrity of the historic environment.

From the standpoint of technological strategy, the most robust outcomes are typically produced by solutions oriented toward minimal invasiveness and modularity: the use of visually unobtrusive routes, localized distribution points, and carefully executed in-unit cabling that can be scaled as approvals are obtained. Combined with proper wayleave formalization and thorough as-built

documentation, this forms a basis for subsequent operation and upgrades without repeated intervention in building structures—an especially important condition for assets where any additional construction impact entails high costs and regulatory exposure.

3.2. Greenfield: Efficiency of Integrated Deployment

In new-construction projects (Greenfield), telecommunications infrastructure is embedded from the outset as an element of the master plan and coordinated with architectural and structural decisions, the transport scheme, and the placement of utility networks. This planning shifts cable installation from a mode of “adaptation to constraints” toward controlled engineering design, where route optimization, capacity reservation, and building readiness for rapid commissioning become central.

A substantial economic effect is created through synergy with general construction and engineering works: duct banks are installed as part of common trenches jointly with power supply and water lines, reducing the share of earthworks costs by 40–60% [27]. Beyond the direct reduction in excavated volumes and reinstatement work, this approach decreases the number of approvals, lowers the likelihood of repeated pavement openings, and simplifies quality control, since core operations are executed within a single production cycle and under unified construction logistics.

The technological standard for Greenfield increasingly shifts toward a Plug-and-Play principle: the use of pre-terminated cable assemblies, factory-prepared endfaces, and microducts embedded in walls and risers during construction enables subscriber activation within minutes—without dust, noise, or additional construction and installation impact inside occupied spaces [28]. As a result, the operating model becomes more predictable: labor required for in-premises installation decreases, the influence of human factors during stripping and fusion splicing is minimized, and connection quality is more controllable due

to factory preparation of elements and standardized commissioning procedures.

The investment attractiveness of new projects is further enhanced by lower CAPEX: there is no requirement to dismantle obsolete systems, and costs associated with finish restoration and compensatory works—typical for retrofits—are absent. Collectively, these conditions improve financial transparency, reduce the share of unforeseen expenditures, and accelerate achievement of target payback metrics, since the network enters service simultaneously with the building asset and begins generating cash flow without prolonged preparatory phases. A figure 2 is provided below to visually demonstrate the difference in project complexity.

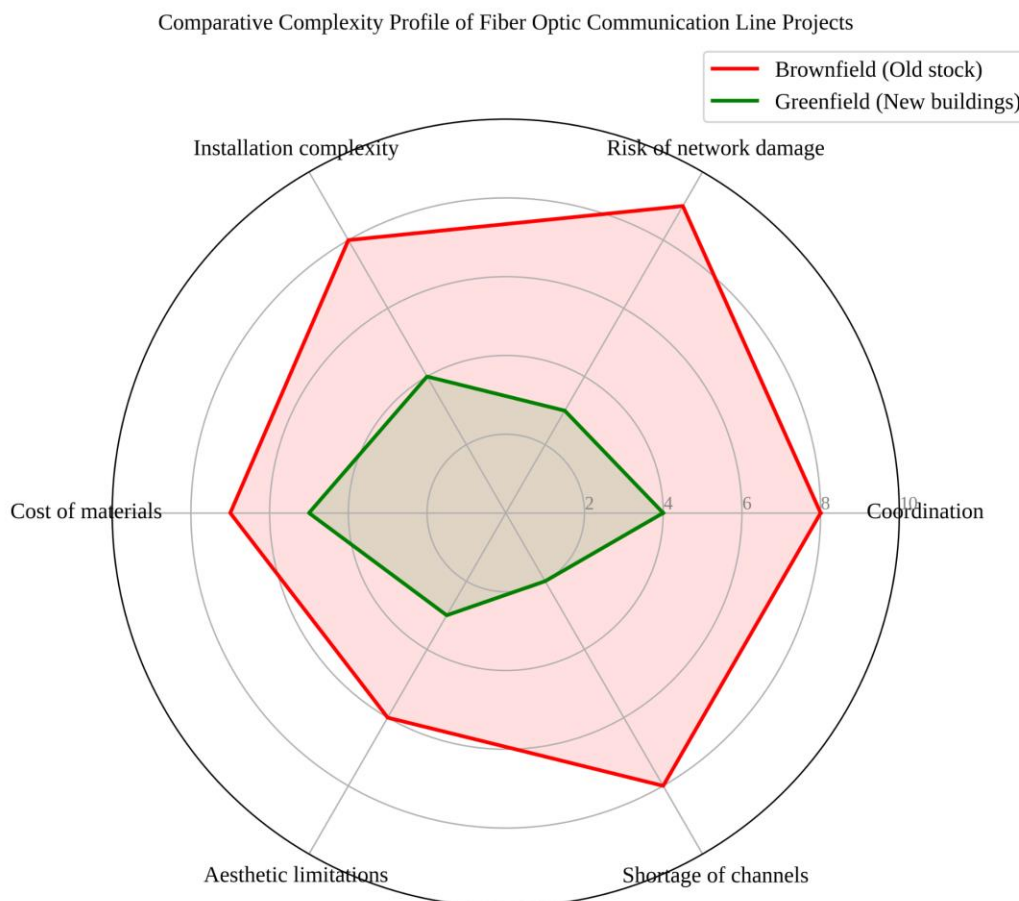


Fig.2. Complexity-Assessment Parameters (10-point scale)

Thus, in greenfield construction projects, an integrated rollout of telecom infrastructure—embedded in the master plan and synchronized with architectural

design, utility systems, and construction-site logistics—shifts cable deployment from reactive “constraint fitting” to controlled engineering design, delivering a substantial economic effect through shared trenching, which can reduce the share of excavation-related costs by 40–60% [27]. Fewer coordination cycles and a lower risk of repeated surface openings follow naturally from this integration, while the transition to plug-and-play practices (pre-terminated assemblies, factory pre-configuration, and micro-ducts embedded in building structures) supports fast, clean subscriber activation, reduces labor intensity and exposure to human-factor variability, and improves the predictability of quality. In combination, the absence of legacy-system dismantling and of finish-restoration expenses reduces CAPEX, increases financial transparency, and accelerates achievement of target payback by enabling network commissioning in parallel with building delivery and by bringing forward cash-flow activation.

CHAPTER 4. ALGORITHMIC OPTIMIZATION AND RESILIENCE

Under conditions where every meter of trench is expensive and any design error can trigger a collapse of a district’s transport system, the application of intelligent planning methods becomes effectively non-negotiable.

4.1. AI-Driven Network Design

Traditional heuristic approaches to telecommunications-network design—relying primarily on an engineer’s individual experience and local “best-practice” rules—tend to exhibit systematic errors once scaled to the megacity level. The effect is most visible in bills of materials and, consequently, in budgeting: the error in the material-cost component may reach 15–20% due to incomplete baseline data, heterogeneity of the urban fabric, high variability of routes, and the accumulation of small tolerances across many interfaces. In response to these limitations, leading companies in 2024 increasingly shift toward machine-learning algorithms and optimization methods for automated routing, including modified Steiner-tree formulations and metaheuristics such as Particle Swarm Optimization, which provide approximations to globally rational solutions at acceptable computational cost [29].

Computer-aided design tools (e.g., Comsof and VETRO) extend this approach by creating a digital environment in which engineering decisions are derived from the integration of geodata and formalized constraints. By connecting GIS layers (building footprints, road network, existing duct infrastructure, restriction zones, and easements), automated generation of network topology becomes feasible: subscriber-base clustering, placement of branching nodes and splitters, and selection of feeder and distribution routes with minimization of total cable length and earthwork volumes [30]. Such a design mode reduces dependence on subjective preferences and supports reproducibility when the model is reused across different territories.

Empirical evidence suggests that transitioning to algorithmizable design can sharply reduce the duration of pre-design and design procedures: development-time reductions may reach up to 90% due to automation of routine operations, faster clash detection, and accelerated specification generation [31]. At the same time, CAPEX reductions of 10–15% are reported, driven by more accurate component selection, lower excess reserves in cable and hardware, and shorter route lengths achieved through system-level exploration of alternative paths within the full set of constraints [31]. A further material effect is improved budget predictability, since material and labor estimates are tied to formal rules and continuously updated data layers rather than averaged coefficients.

Methodologically mature implementations complement optimization with validation mechanisms and structured management of uncertainty in the source information. Practical workflows include calibrating the model against actual construction and operations data, applying scenario analysis for zones with high utility density, and introducing penalty functions for risk-prone segments (crossings, protection zones, complex soils). In this configuration, automated design ceases to be a mere “diagram generator” and becomes an instrument of controlled choice, where network topology, asset placement, and life-cycle cost are coordinated within a single computational formulation, and decision quality is supported by comparison with measurable implementation outcomes.

4.2. Disaster Resilience and Catastrophe Resilience

Urban fiber-optic networks are exposed to damage not only from excavation activities but also from natural impacts whose scale intensifies against the backdrop of climate change. Flooding, storm winds, and other extreme events shift resilience from an auxiliary parameter to a foundational infrastructure-quality indicator. Underground placement of cable lines, on average, demonstrates substantially higher weather resistance than aerial deployment: specialized studies note that underground infrastructure experiences 78% fewer

outages, which is explained by lower exposure to wind loads, icing, and falling trees, as well as a more predictable operating regime [32].

Increased survivability is achieved through a combination of topological and technological measures. Redundancy of backbone segments via ring topology enables connectivity to be maintained when one segment is severed and reduces the probability of total failures within a served cluster [33]. In parallel, intelligent monitoring systems based on Distributed Acoustic Sensing (DAS) are being introduced, where the optical fiber functions as a distributed vibration sensor: AI-based recognition algorithms can identify characteristic signatures of heavy machinery operating near the route and issue warnings prior to physical cable damage [34]. For catastrophic-destruction scenarios—when extended sections of cable infrastructure become inaccessible—hybrid schemes are applied involving temporary inserts based on free-space optical (FSO) channels or networks supported by high-altitude platforms (HAPS), integrated with surviving fiber segments to accelerate restoration of connectivity [36].

An additional resilience reserve is established at the engineering-design stage through risk-oriented routing and constructive measures aimed at preventing secondary damage. Practical implementation includes separating routes across independent corridors, avoiding “common points of failure” (shared manholes, crossings with critical utilities, vulnerable bridge transitions), and accounting for hydrogeological factors: flood-prone zones, groundwater-level fluctuations, and probable water-migration pathways along underground structures. Passive-protection elements are also significant—sealing of closures and entries, application of water-blocking constructions, provision of service loops, and correct placement of branching nodes outside maximum-risk zones—since localized nodes frequently become “bottlenecks” during post-incident restoration [35, 37].

Operational readiness is no less important: network resilience is determined not only by how rarely damage occurs, but also by how quickly and

controllably restoration is executed. For this purpose, emergency-response procedures are established, prioritization schemes are defined, critical-material reserves are maintained, and preplanned traffic-switching scenarios are prepared, including regular verification of bypass-route functionality and automatic/semi-automatic reroute procedures. Within the monitoring domain, an appropriate balance between sensitivity and reliability is required: DAS systems improve early threat detection, yet effectiveness depends on model-training quality, triggering thresholds, and integration with dispatch operations in order to minimize false alarms and ensure practical applicability in a 24/7 mode.

CONCLUSION

The research results support the stated hypothesis and enable generalized conclusions that reflect a shift in the sectoral paradigm toward intensive, minimally invasive, and data-driven practices. Under conditions of high-density urban development, the resource base of extensive construction has effectively been exhausted: traditional approaches based on large-scale earthworks demonstrate a deteriorating ratio of schedule, cost, and externalities for the urban environment. In this configuration, micro-trenching technologies emerge as a dominant development direction because—despite objective constraints, including climate-driven risks—they provide the most rational compromise between deployment speed and project economics; an indicative unit-cost range of approximately USD 10–15 per foot simultaneously reduces financial burden and minimizes the destructive impact of works on city functioning.

An effective strategy for deploying optical infrastructure requires a fundamentally differentiated project approach depending on development type and baseline engineering conditions. For new construction (Greenfield), the technologically optimal and economically justified standard is full integration of passive infrastructure during the construction stage, enabling advance formation of routing, building-entry nodes, and redundancy while reducing CAPEX uncertainty. For existing housing stock (Brownfield), universal scenarios are virtually absent: individualized engineering dominates, implying the use of microcables and non-invasive installation methods that minimize intervention in structural and façade elements. This logic unavoidably increases project cost; however, in certain cases it is partially offset by the growth in an asset's consumer value and, consequently, by higher real-estate capitalization due to improved digital availability and service quality.

A critical factor for improving efficiency is the role of data: design of urban networks increasingly ceases to be an exclusively construction-centric discipline

and acquires the characteristics of Data Science–class problems. The use of GPR surveys for forming digital twins of the subsurface environment, together with AI-based algorithms for route-optimization and detection of conflicts with existing utilities, reduces the share of uncertainty associated with “hidden works” and enables reduction of the risk premium embedded in estimates, supporting budget optimization at the 10–20% level.

Taken together, the results indicate that sustainable development of a modern city’s optical infrastructure is achievable only through coupling micro-invasive construction technologies, a precise accounting of housing-stock specificity, and a developed analytical foundation capable of supporting substantiated decisions across all stages of the project life cycle.

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