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Original Research Article

Strategic Deployment Challenges and Optimization of FTTH/FTTX Networks in Saudi Arabia under Vision 2030

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Abstract: Fibre to the home and broader FTTX programmes are central to the digital transformation of Saudi Vision 2030, but large-scale implementation is presently hindered by the cost of civil works, permitting, fibre corridor congestion, and the need to ensure quality over long periods of delivery. This systematic review combines evidence published during 2020-2025 on FTTH/FTTX implementation challenges and optimization approaches, with a focus on the Saudi delivery context. Following PRISMA guidelines for screening and thematic synthesis, articles are grouped into five themes: programme management and right-of-way (ROW) challenges; GIS planning and outside-plant (OSP) optimization; construction methods and quality assurance; PON capacity building and migration planning; and operations, resilience, and sustainability reporting. A reference architecture is described that combines Vision 2030 ambitions, geospatial planning, build telemetry, and operations feedback into a closed-loop optimization process. Throughout the synthesis, the most successful approaches are socio-technical: permitting automation, design rule checking, build productivity analysis, and data-driven compromises between speed and lifecycle risk. The paper concludes with a logistics-driven research agenda for Saudi Vision 2030 programmes, emphasizing quasi-experimental studies, cost-per-foot accounting, and corridor governance models for mega-projects.

Keywords: FTTH, FTTX, Fibre Deployment, GIS Optimization, Microtrenching, PON Migration, Saudi Vision 2030, Governance, Logistics, Resilience.

INTRODUCTION

The role of digital infrastructure development in the promotion of economic development and the development of the public service sector is emphasized in the Vision 2030 strategy of Saudi Arabia. Fixed high-capacity networks are emphasized as one of the most fundamental areas, as fiber access infrastructure is emphasized as one of the most fundamental building blocks for capacity development, 5G backhaul densification, cloud computing, and low-latency public sector applications. The role of fiber access and gigabit network development is emphasized in the Saudi government reports as part of an "advanced connectivity vision" (MCIT, 2024). Globally, the role of fiber infrastructure development in the promotion of improved broadband quality of experience and digital industry readiness is emphasized, making FTTH/FTTX a fundamental "general purpose" infrastructure (FTTH Council Europe, 2022). The development of fiber infrastructure at the national level is still a challenge. The cost survey data have always indicated that the civil works cost is the most fundamental factor in fiber costs, and permitting/make-ready risks are a fundamental basic schedule and cost risk (Fiber Broadband Association & Cartesian, 2024). In the urban area, these are congestion in existing utilities, surface restoration, and restrictions on disturbing public space. In the suburban and rural areas, these are distance, low density, and terrain variability, making business cases and logistics schedules difficult. These are further complicated in mega-project plans with tight schedules and, at the same time, the construction of various utilities. From an engineering point of view, the present FTTH/FTTX infrastructure is mainly composed of a PON structure, and splitter design, routing, and duct re-use techniques are thought to have an essential role in CAPEX. In assessing the future viability of PON networks, it is imperative to focus on the migration strategy for the electronics (XGS-PON and range extension migration strategy) without inquiring about the details of the costly civil engineering (ITU-T, 2023; ITU-T, 2022). The next challenge is therefore systems integration: program management, geospatial planning, construction implementation, and operational reporting must be integrated into one delivery system, as opposed to being distinct processes. While there is an ever-expanding literature base on techno-economic models, GIS planning, and construction best practices, the literature base is surprisingly disconnected and unaligned with delivery governance. This review therefore, fills the gap through offering a logistics-focused framework for 2020-2025 evidence on Saudi Vision 2030 delivery, including a framework for a reference architecture and evidence map.

METHODOLOGY

Aim

The aim is to acquire information on tactical deployment challenges and optimization methodologies pertinent to FTTH/FTTX, with a focus on the delivery strategy of Saudi Vision 2030, which is set to be deployed from 2020 to 2025.

Objectives

O1: Identify the major factors affecting costs, project schedule risk, and quality issues pertinent to ultra-large-scale FTTH deployment.
O2: Investigate optimization methodologies pertinent to OSP network planning and their association with deployment challenges.
O3: Include construction methodologies and quality control strategies with minimum rework and error rates.
O4: Compile information on PON evolution and migration methodologies pertinent to FTTH/FTTX networks, with a focus on the entire operational lifecycle.
O5: Develop a reference architecture with relevance to the private and public sectors.

Research Questions

Figure 1, which is presented below, illustrates a reference architecture for FTTH/FTTX, which can be considered an efficient closed-loop deployment process with interconnected processes and systems that ensure the efficient deployment of FTTX services and facilities. The reference architecture developed in this study is presented to set the context for the proposed thematic synthesis, which is presented in the following sections. Figure 1 illustrates the framework in which the proposed analysis is performed.

The research design of the proposed study follows a systematic review and thematic synthesis methodology. The inclusion criteria for the proposed study are based on the PRISMA 2020 protocol, which ensures transparency in the selection, evaluation, and inclusion of studies (Page *et al.*, 2021). The literature review for the proposed study was conducted between 2020 and 2025, and the sources are classified into four types: (a) literature on FTTH/FTTX planning and techno-economic analysis, (b) authoritative literature on optical access interoperability standards, © literature on the cost structure, construction methods, and sustainability of FTTH/FTTX, and (d) Saudi Arabian governmental literature on policy and sectoral analyses related to fixed broadband management and development in the country. The search terms are classified into four types: (a) technology-related terms, (b) planning and optimization-related terms, © construction-related terms, and (d) regulation-related terms. The inclusion criteria for the proposed study are related to deployment results, and the exclusion criteria are related to ignoring literature that is irrelevant, out of date, and not pertinent to deployment results. The literature for the proposed study is classified into five themes.4. Graphical Representation: Reference Architecture.

Research Gaps and Agenda

G1: Causal evaluation **-** Enhance quasi-experimental designs for permit reform, micro-trenched specifications, and other related domains.
G2: Standardized Cost Accounting- Unpack the cost per meter into engineering costs, permitting costs, make-ready costs, restoration costs, and rework costs.
G3: Building Telemetry Interoperability**-** Enhance the quality of data provided by contractors.
G4: Mega-project Corridor Logistics- Remove conflicts in scheduling for megaproject corridors.

G5: Resilience Modeling- Determine the OSP factors that must be quantified in terms of outages and repairs that must be addressed in the future.

G6: Sustainability Baselines- Provide transparency on localized data to evaluate construction practices based on disruptions.

Thematic Synthesis

Programme Governance, Permitting, and ROW Coordination

Fibre programme governance is a thematic issue that is associated with municipal access, traffic, utility issues, and restoration. The analysis of the costs shows that permitting and make-readiness might be significant programme costs, although the construction volumes are within manageable levels. The international best practice for programme governance, as stipulated by the ITU, indicates that programme governance and inter-agency coordination are fundamental for the sustainability of broadband programmes. In the Saudi Arabian industry literature, open access and infrastructure sharing have been identified as methods for facilitating the acceleration of the deployment of access infrastructures, which reduces costs and hence the likelihood of duplication. This indicates that programme governance needs to be designed to accommodate multi-operator coordination and not single operators. In the analysis, three programme governance issues have been identified as controllable: permitting of service level agreements for front-end management, coordination of corridors or the use of the concept of "dig once," which involves the coordination of fibre deployment and roadworks and utility works, and restoration quality, defect closure time, and as-built data quality, which serve as contractor performance measures that link programme management to programme outcomes. These issues have significant relevance to the programme governance of the Saudi Vision 2030, which involves the coordination of utility works and disruption.

GIS Planning and OSP Design Optimization

The design variables of an OSP have a substantial impact on the overall economics of a fiber network due to their effect on the excavation depths (radius), duct re-usage, number of splitters/cabinets included in the design, and so forth. The results of the optimization of the OSP design problem to date show that ILP/MILP formulations of PON design problems have been successfully solved to determine the equipment site locations where costs are minimized while fulfilling engineering and coverage constraints (Al Romaithi *et al.*, 2020; Alkhajeh, 2022). The solutions of the GIS design play a vital role in meeting these objectives while considering road geometry, demand locations, and other utility requirements, as well as providing traceability of the design to as-built status. Recent case analysis results of the application of the GIS design solutions highlight the significance of geography-informed design solutions in solving the PON design problems pertinent to real-life contexts (Vargas-Bustamante *et al.,* 2025). The implementation of the programme optimization needs to be constrained. Without constraints, the benefits of cost savings from the optimization could be offset by the costs of unregulated route digging and splicing. The constraints critical to the PON network design include design constraints having traceability, such as loss budgets, splitter ratios, spare capacities, duct reusage priorities, and so forth. Interoperability tools are highly beneficial in providing guidance in the implementation of the programme, as they help avoid vendor lock-in risks when providing operational onboarding, as indicated in the interoperability test plans for PON networks (Broadband Forum, 2024).

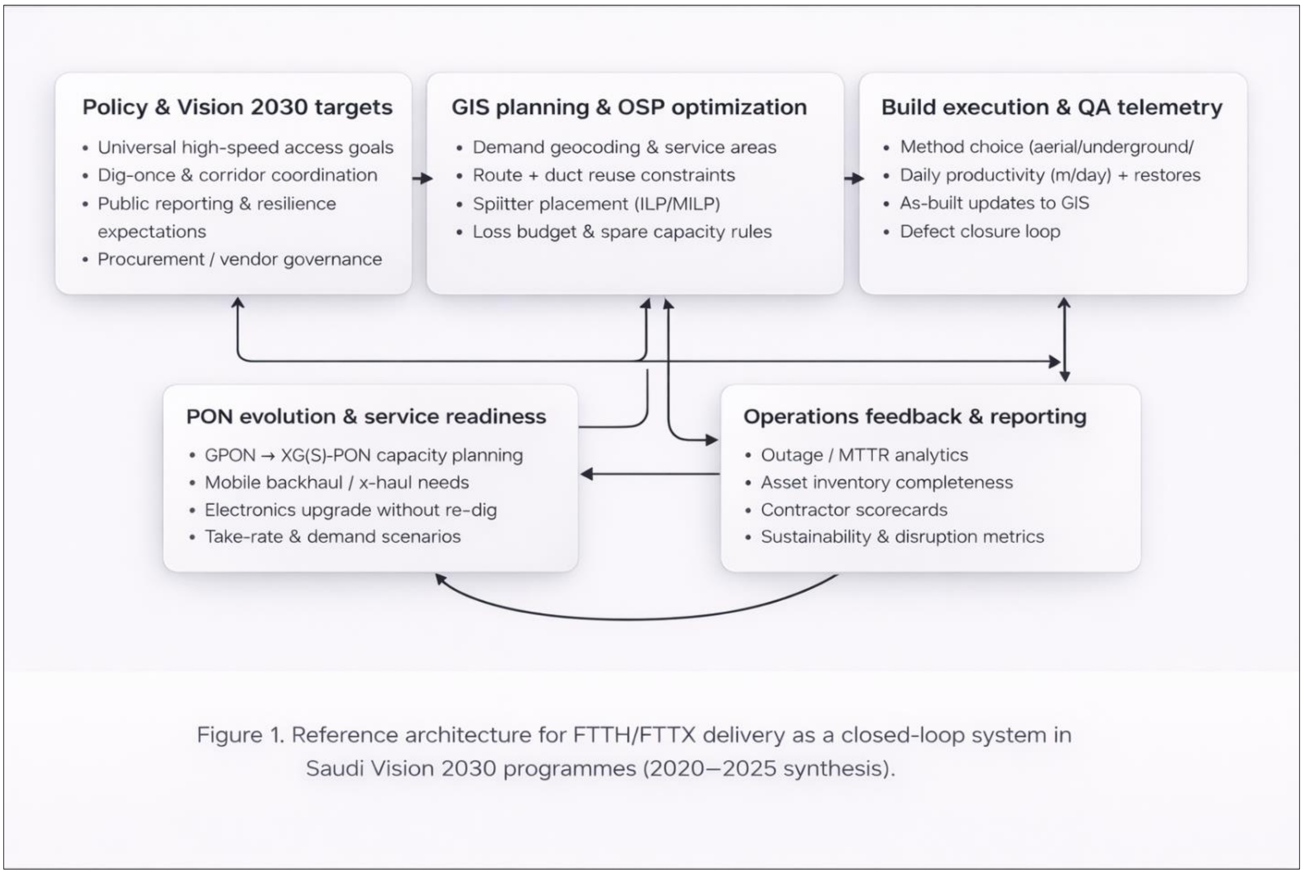

Figure 1. Reference architecture for FTTH/FTTX delivery as a closed-loop system in Saudi Vision 2030 programmes (2020–2025 synthesis).

Figure 1: Reference architecture for FTTH/FTTX delivery as a closed-loop system in Saudi Vision 2030 programmes (2020–2025 synthesis)

Figure 1 illustrates a reference architecture for FTTH/FTTX with a closed-loop deployment process. Vision 2030 policy agendas and corridor management drive GIS planning and OSP optimization; agendas drive the facilitation of build execution telemetry and quality assurance; and operational data drive changes to standards, contractor performance, and future planning assumptions. The reference architecture is included here to introduce the thematic synthesis that follows.

Location: Insert Figure 1 in Section 4, before Section 5 (Thematic synthesis). Research questions:
RQ1: What are the most major constraints that have forced FTTH/FTTX projects to go into overruns and delays?
RQ2: What are the metrics and reporting approaches that have been most successful in sustaining performance in multi-year national programs?

Construction Methods, Microtrenching, and QA

The major challenge for the widespread adoption of fibers isn't the technology but the construction process. If you compare the cost of building fibers to building them through the air, the cost varies greatly depending on the construction method, such as microtrenching, and the restoration of the road or the sidewalk. The basic principle behind the construction process is to ensure that the trenches are narrow and the restoration process accurate so that you don't have to redo them later, as it would cost you dearly. The Vision 2030 report states that faster construction only gets you more time, not cost savings. However, the issue of QA can cause faults or outages. For the construction of government projects, the use of construction telemetry can be important as the early warning signs will appear as anomalies in the process metrics. For instance, it can reflect the rate at which defects are being closed.

PON Evolution and Migration Planning

While the construction process can take decades, the electronic parts can change within only 3 years. Therefore, the construction process should take about 5-10 years to ensure that it can accommodate changes and upgrades without the need for excavation (Fiber Broadband Association & Cartesian, 2024). ITU-T has identified PON technologies for reach and capacity (ITU-T, 2023, 2022). The use of interoperability frameworks such as the Broadband Forum Test Plans can help you save on integration costs (Broadband Forum, 2024). Migration should also take into account the cost of the technology through cash flow and sensitivity analysis (Skoufis *et al*., 2023). In Saudi Arabia, the speed at which people and businesses get connected is important. This can be seen through the drive for widespread, gigabit-class fixed connectivity, as outlined in the MCIT (2024) plan. This can also be seen through the drive for increased mobile network capacity through large capacity links, as seen through the drive for x-haul solutions and the move towards increased use of fiber for backhaul. As such, the use of fiber networks and the drive for increased speed through the use of fiber connectivity will become the new backbone for the transport layer (5G Americas, 2023).

Operations, Resiliency, and Sustainability Reporting

As the fiber network digs deeper into the country, the level of interest from the public will grow, especially when the use of digital government or business operations is hindered through network outage. This can be seen through the research into connectivity, which has already shown the lack of fixed broadband connectivity (ITU, 2022; ITU, 2023). Looking at the digital regulations for Saudi Arabia can point the way for increased investment, regulatory collaboration, and the drive for telecommunications modernization to grow the industry (Digital Regulation Platform, 2023). This will point to the level of digital reporting maturity. With the move towards open access and infrastructure sharing, the level of need for accurate infrastructure reporting will become more important (CITC, 2021).

In terms of sustainability, the use of fiber connectivity will play a major part in the reduction of the level of power required on a per bit transmitted (Fiber Broadband Association, 2024). The association's white paper compares the footprint of FTTH against other upgrade options. As the operations reporting grows within Saudi Arabia, the traditional performance reporting will continue to grow, such as outage minutes, MTTR, restoration defects, permit lead times, build rates, and rework rates, as well as sustainability reporting such as work front disruption rates, all of which will align to the Vision 2030.

Evidence Map and Metrics Framework

This section connects the constraints, levers, and metrics related to good governance. As can be seen from the literature reviewed from 2020 to 2025, it is not just about counting fibers in the infrastructure to determine good governance. To ensure good governance in Saudi Arabia, we must identify what metrics can give us an insight into where we are losing time and money. This is in line with the cost survey, which breaks down costs to include engineering, permitting, labor, materials, make-ready, traffic, restoration, etc. (Fiber Broadband Association & Cartesian, 2024).

To meet the requirements of the Saudi program, we propose a five-layer KPI framework to ensure good governance in Saudi Arabia. These include:

L1: Governance KPIs: These include KPIs related to policy, corridor-related issues, permits, corridor conflict, restoration, etc. This is particularly important at the moment, given that the sector is under policy review (Digital Regulation Platform, 2023).

L2: Planning Process KPIs: These include KPIs related to planning, design to build variance, duct reuse, feeder utilization, splitter ratio, optimization in spite of external factors, etc. (Al Romaithi *et al*., 2020; Alkhajeh, 2022).

L3: Execution Process KPIs: These include KPIs related to execution, meters built per crew per day, rework, defect closure, safety incidents, etc. (MAG/TTI, 2024).

L4: Service Activation KPIs include time to activation, customer readiness, and first-time-right splicing (Broadband Forum, 2024).

L5: Operations KPIs: Outage minutes, MTTR, fault rate per km, and asset registry completeness, which can be used for design standards or contractor scorecards (ITU, 2023; CITC, 2021). It is possible to audit the data model, as it has a unique ID for each network segment, along with other attributes such as location, construction type, restoration status, and acceptance status. The faults will also be linked to the segments, thus providing a feedback loop for fault rate, micro trenching, and construction variances.

Optimization Models and Decision Levers

We can optimize several construction variables to improve the overall OSP construction process. For OSP construction, we can optimize the construction process as follows:

a) Service Area Partition: Divide the service area into service nodes considering reach, loss, and cabinet practicality.
b) Routing: Plan the routes from the hubs to the demand clusters.
c) Splitter Hierarchy: Determine the level and ratio of splitters, central or distributed.

The optimization model's strength lies in its sensitivity analysis feature. The ILP/MILP can optimize costs while considering constraints such as civil costs, ducts/microducts, fiber cables, closures/splices, cabinets, splitters, electronics, and permitting/restoration. Civil costs are the major cost for OSP construction, followed by trench and duct reductions and construction risks. Permit costs will dominate overall costs (Fiber Broadband Association & Cartesian, 2024). The restoration cost will increase due to the heat conditions in Saudi Arabia. The restoration cost can also be included as an objective function parameter.

ILP/MILP Constraints:

a) Coverage: The network must cover all demand points.
b) Capacity: The capacity of the fiber allocated to the feeder or distribution network should have enough capacity to support the demand points within the duct capacity.
c) Optical: The parameters should fall within the specification of the parameters of the optical fiber.
d) Resilience: Optional routing should consider ring feeder configurations to key nodes.

These constraints are in line with Vision 2030 standards regarding durability in the public sector, especially in terms of business continuity. The Vision 2030 report indicates that power outages have a negative impact on digital government services, education services, and health services in Kenya (ITU, 2022; ITU, 2023). Subsequent construction after the deployment of the telemetry system could also be considered in the optimization model. Best practices in terms of micro-trenching could also be considered in the optimization model. For instance, risk-based inspection levels could be considered in the optimization model in areas considered to be at a higher risk of construction, especially in terms of roadways (MAG/TTI, 2024). Permitting could also be optimized in terms of a dashboard that could be integrated with policy levels in the governance structure. Migration could also be considered in the optimization model. ITU-T evolution could be considered in terms of upgrading electronics in the same optical network in terms of capacity upgrades to the OLT/ONU through the adoption of new feeder routes. A techno-economic analysis reveals uncertainty in terms of take rates and demand growth rates, which are important in terms of decision-making (Skoufis *et al.*, 2023). Scenario planning could influence the optimization model in terms of avoiding overbuilding while at the same time following Vision 2030 directives regarding megaprojects and milestones in Kenya. The optimization system should be clearly understandable in terms of the governance structure in Kenya. It should also be auditable in terms of the assumptions used in the framework, similar to the verification of the telemetry system.

Challenge / constraint	Typical root causes	Optimization / control lever	Operational metric (examples)	Representative 2020–2025 sources
Permitting & ROW delays	Fragmented approvals, utility conflicts, restoration disputes	Standardized permit workflow; corridor coordination (dig-once)	Permit lead time; % rework due to conflicts; restoration defects	ITU (2020); NCC/MCIT (2022); FBA & Cartesian (2024)
High civil-works cost	Labour/material inflation; trench method choice; make-ready	Technique selection (aerial vs underground vs microtrench); productivity benchmarking	Cost/foot by method; labour share; make-ready %	FBA & Cartesian (2024); MAG/TTI (2024)
Suboptimal OSP design	Manual planning, poor GIS, uncontrolled field changes	GIS routing + ILP/MILP placement; auditable design rules	Feeder utilization; splitter ratio compliance; design-to-as-built variance	Al Romaithi *et al.*, (2020); Alkhajeh (2022); Vargas-Bustamante *et al.*, (2025)
Lifecycle quality failures	Weak QA on restoration, shallow placement, water ingress	Risk-based inspection; restoration specs; defect closure loop	Faults per km; repeat digs; restoration acceptance rate	MAG/TTI (2024)
Unclear migration economics	Reactive upgrades, weak demand forecasting	Techno-economic migration modelling; staged investment planning	NPV/IRR scenarios; take-rate sensitivity; electronics swap frequency	Skoufis *et al.*, (2023); WBBA (2022)
Resilience & reporting gaps	Incomplete inventory, long repair cycles, KPI fragmentation	Unified asset registry; O&M analytics; public reporting alignment	MTTR; outage minutes; asset completeness; ESG indicators	MCIT (2024); ITU (2022); ITU (2025); FBA (2024)

DISCUSSION AND FUTURE OUTLOOK

Optimizing the fiber network is not merely an exercise on paper but the whole process from rollout to deployment and further optimization throughout the entire lifecycle of the project. Looking into the future with the Vision 2030 initiative, we have identified the areas of focus for the next stage of the project rollout, which include the management of duct corridors, designing fibers in line with the rollout strategy, further optimization of the algorithm with the experiences gained during the rollout process, and the determination of restoration speeds and redundancy in line with security requirements (OECD, 2025).

Saudi Vision 2030 Deployment Scenarios and Practical Optimization Priorities

Fiber rollout is not the same everywhere, and the differences play an important role in the optimization process. For the Saudi Vision 2030 initiative, the deployment scenarios have been identified as (S1) Dense Urban Infill, (S2) Suburban/Rural Expansion, and (S3) Giga Project Corridors/Growth.

S1: Dense Urban Infill

The objectives of the dense urban infill deployment include the reduction of travel time, minimizing disruptions, avoiding hazardous areas, and utilizing existing infrastructure. In terms of governance, standardizing restoration acceptance and pavement liability can result in cost savings. In terms of optimization, the use of micro trenching is beneficial when used in line with best practices (MAG/TTI, 2024). The heart of the optimization process is the determination of the risk score based on pavement condition, traffic, and density of the utilities in the area.

S2: Suburban and Rural Expansion

The major drivers in the suburban and rural expansion rollout include trench length, take rate, and backbone costs. The Global Linkage Report identified the feasibility of suburban and rural rollout with reasonable take rate without the need for infrastructure (ITU, 2022). The optimization process aims for the reduction of feeder costs by clustering the infrastructure in line with the need to minimize the distance to the premises. Open access is essential in avoiding duplication of infrastructure, and the Saudi sector report identified open access as an essential step in the rollout process (CITC, 2021). Architectural forecasts must include scenarios instead of the use of the take rate in line with the techno-economic best practices (Skoufis *et al.*, 2023).

S3 gives us a wide view of the Giga project corridors in the Vision 2030 plan. It gives us a wide view of the logic that has been used in the design findings that have been made along the way and shows how a "dig once" approach was also considered to revisit them in the future. However, the plan has to be compatible with the project timeframes to keep the safety aspect in check and to be able to deliver all the services in parallel. Sustainability reports give us a wide view of the future infrastructure requirements that have to be met. Although wide in scope, covering the entire NEOM region (2023), there is a need to identify the type of infrastructure that will be needed in the future. We will need the infrastructure to provide the required fiber to support fixed, enterprise, and mobile transport services, as indicated in the transport guidelines, to provide a dense radio access network and edge services, which will be required to deploy 5G networks, as indicated in 5G Americas (2023). We will need the ability to support the existing transport requirements. The link between all of the above points has been the auditable data model that is a part of the Saudi initiatives. This brings together the key elements of the process, including geometry and identity, contractor productivity, restoration defects, and closure of defects, to name a few, and creates the basis of a process that will enable design rules and build processes to be harnessed to combine all the participants of the process seamlessly. There is a requirement to understand the test plans to combine the civil infrastructure, as stated in Broadband Forum (2024) and ITU-T (2023). The most important thing to remember in this regard is that the splitter ratios, cabinet capacity, and reserved ducts hold to be "built once, upgraded many times."

Managerial Implications and Implementation Roadmap

The following roadmap is broken down into four phases.

Phase 1: Visibility & Corridor Governance

- Develop a common asset hierarchy, corridor basemap, and permit package with lead times.
- Promote the use of shared infrastructures and restoration thresholds. (Source: CITC, 2021; ITU, 2020)

Phase 2: Auditable Design Optimization

- Utilize GIS routing and ILP/MILP for the optimization of the splitter nodes and feeder cables, considering environmental aspects. (Source: Al Romaithi *et al.*, 2020; Alkhajeh, 2022)

Phase 3: Execution Telemetry & QA

- Monitor micro-trenching, busy corridors, and long-term pavement ownership, adhering to best practices. (Source: MAG/TTI, 2024)

Phase 4: Operations Feedback & Continuous Improvement

- Leverage trouble tickets, outage types, and contractor performance cards.
- Integrate Vision 2030 KPIs. (Source: MCIT, 2024; ITU, 2023)

CONCLUSION AND RECOMMENDATIONS

The FTTH/FTTX rollout in Vision 2030 can be considered as a closed-loop delivery process that combines governance, optimization, build, and feedback. From the evidence available from 2020 to 2025, the most significant drivers for cost and time are civil construction and permitting, and the most significant drivers for quality are restoration, accuracy, and strict design principles. Optimization methods such as GIS routing and ILP/MILP splitter location are most beneficial when combined with auditable governance and construction telemetry that can identify drift early. The first recommendation for projects that are based in Saudi is to use a process architecture that is closed-loop, where policy objectives and corridor governance drive standardized planning, planning drives verifiable construction, and feedback from delivery drives improvement. This will ensure that the development of the fiber infrastructure is well-aligned with the delivery needs of Vision 2030 and that public sector service sustainability and enterprise competitiveness are enhanced.

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