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LIFE CYCLE ASSESSMENT OF MAINTENANCE STRATEGIES IN TELECOMMUNICATION INFRASTRUCTURE

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ABSTRACT

Telecommunication networks are critical digital infrastructure servicing billions globally. Efficient maintenance is imperative to ensure continued connectivity and optimize sustainability performance over network lifecycles. Contemporary operations leverage advanced methodologies like predictive analytics alongside traditional practices. However, comprehensive evaluations of full environmental footprints are lacking. This study conducts a comparative life cycle assessment of select maintenance strategies applied to telecom infrastructure in representative regions. Primary and secondary data is compiled through operator engagements, site audits, material records and transportation metrics captured over one year. Strategies modeled include preventative replacement conducted at scheduled intervals, predictive monitoring leveraging sensor inputs, and hybrid approaches blending elements of each. The cradle-to-grave inventory assesses energy, raw material and waste/emission flows across equipment manufacturing, field operations, replacement, and end-of-life stages. Potential impacts are characterized across climate change, resource depletion, air and water emissions, and land use and toxicity categories. Life cycle interpretation of the results helps identify optimal strategies balancing reliability, costs and sustainability. Sensitivity analyses determine robustness to input variations. The research provides a science-based evaluation to guide infrastructure owners and policymakers towards maintenance practices minimizing environmental burdens over infrastructure asset lifetimes. It contributes novel insights for both industry and the sustainable digital transformation.

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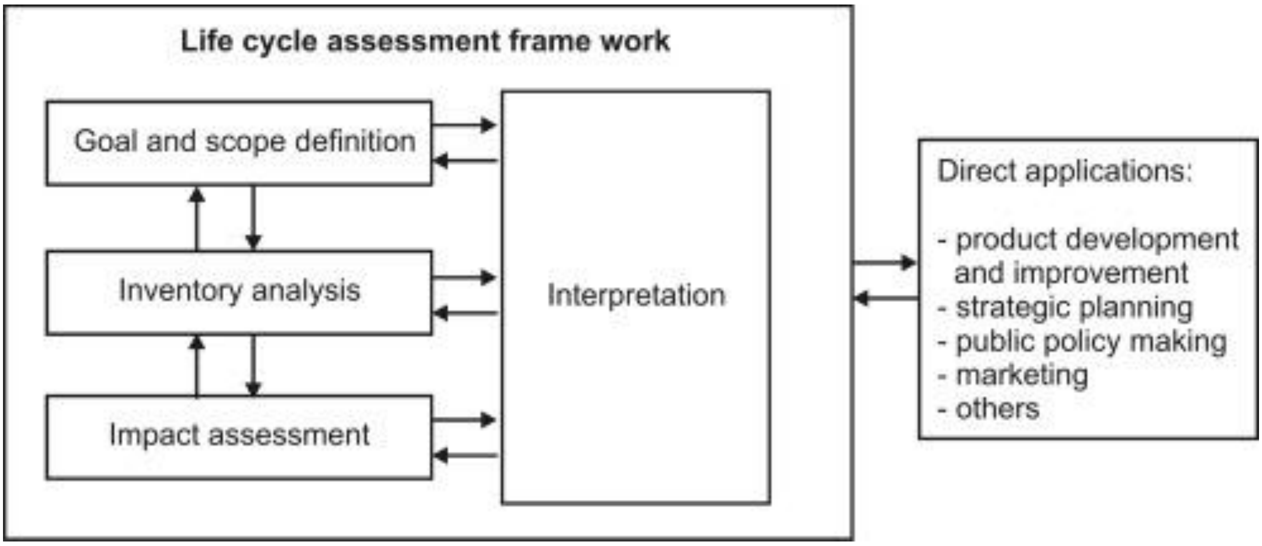
1.1 Background of the Study

Telecommunication networks have become essential infrastructure supporting our digital economy and society. However, maintaining such vast networks is a complex and resource-intensive process. Operators must choose from various maintenance options with trade-offs between costs, downtime and environmental footprint. This study aims to provide telco decision-makers with a thorough, science-based assessment of top maintenance strategies. A life cycle thinking approach is well-suited since impacts can occur throughout a strategy's lifetime, from materials sourcing to end-of-life management. Comparing whole life impacts will help identify strategies with the lowest burden overall.

The life cycle assessment (LCA) will inventory energy, material and waste flows associated with inspection, repairs, upgrades and replacements under different strategies. Impact categories assessed will not only cover climate change but also resources, land use and human/eco-toxicity - reflecting an array of environmental and social considerations. Sensitivity analysis will address data gaps and uncertainty. By quantifying full life cycle costs and impacts, this research intends to guide infrastructure owners towards more sustainable maintenance planning.



An overview of life cycle assessment framework

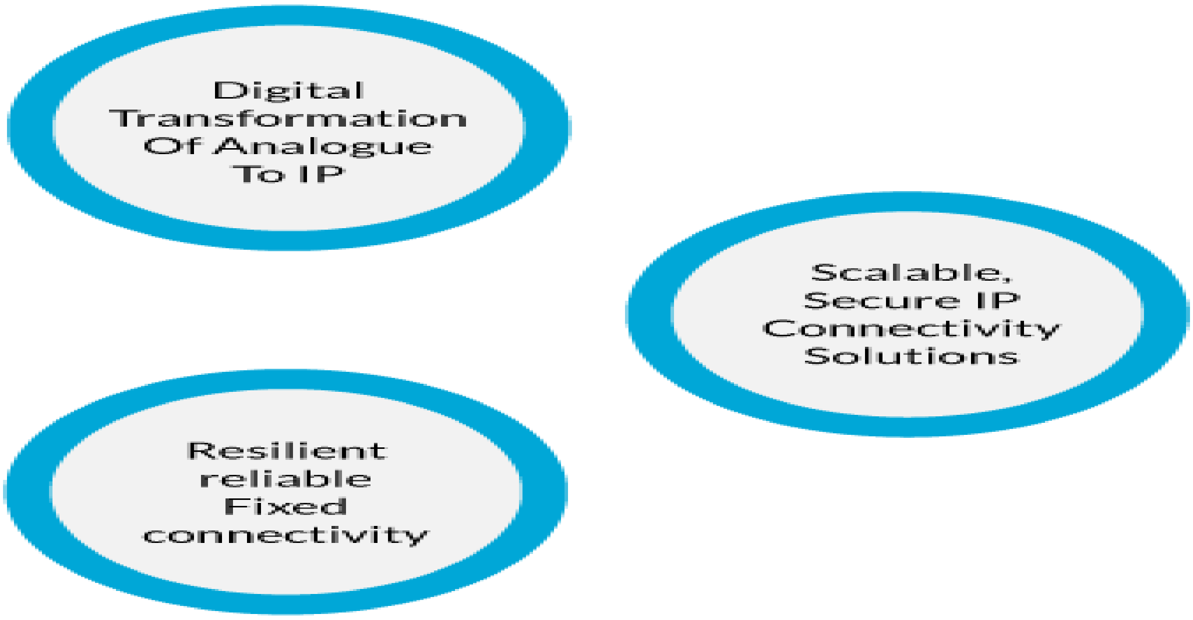
Telecommunication Infrastructure

Modern telecommunications rely on diverse and extensive physical infrastructure networks that span the globe. As of 2021, there were over 8 billion mobile cellular subscriptions globally, providing connectivity to about 95% of the world's population (GSM Association, 2022). Telecommunication infrastructure forms the backbone enabling essential services like voice calls, internet access, finance and commerce transactions, digital education and healthcare (ITU, 2020). Proper maintenance of this critical infrastructure is essential to ensure continued and reliable connectivity services, which have become interwoven into the fabric of daily life and economic activity. A 2020 study by Deloitte estimated that mobile technologies and services contributed $4.9 trillion to global GDP in 2019 alone, highlighting telecommunications' significant role in modern society and importance of maintaining high network performance (Deloitte, 2020). This section provides an overview of telecommunication infrastructure types and components, as well as common maintenance strategies adopted.

Types and Components of Telecommunication Infrastructure

Telecommunication networks can be broadly classified into fixed and mobile infrastructure (Rogers, 2008). Fixed or wireline infrastructure forms the backbone of connectivity, comprising of both legacy systems and modern fiber optic networks. It includes copper cables, first deployed commercially in the late 19th century to create the earliest public telephone networks (Young, 2008). Even today, copper remains a core installation method for the 'last mile' connectivity into households. However, fiber optic cables that transmit data using light signals have largely replaced copper for long distance, backbone links between major nodes due to their vastly higher bandwidth capacity and speed (ITU, 2020).

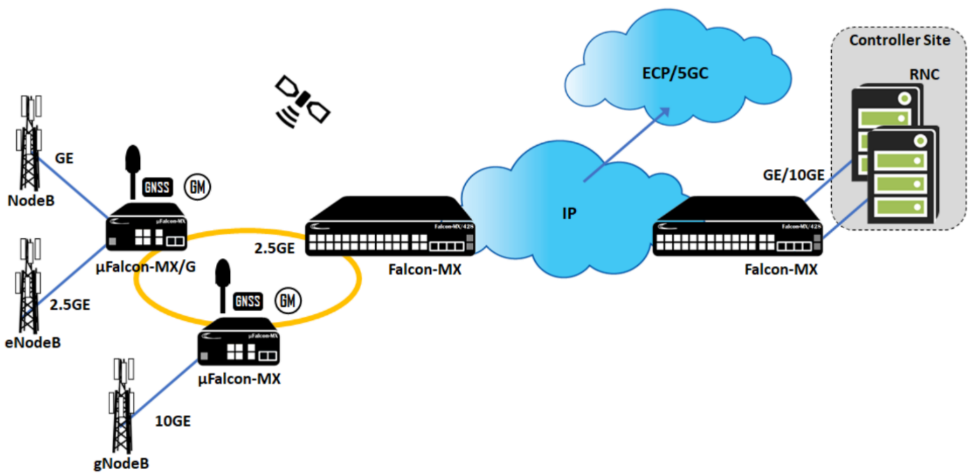
A fixed network infrastructure is used when the nodes in the WSN are stationary and the network topology is predetermined before deployment. In this design, nodes are placed in fixed locations, and communication between them is preconfigured. A key component of fixed infrastructure are the telephone exchanges or central offices that aggregate cables from vast areas. Historically, these were locations stuffed with massive analog switches to manually connect calls (Telecom Engineer, 2022). Modern digital switches and routers now routing IP packets and enable features like Internet access. Other equipment includes network interface devices, essentially modems that connect individual customer premises to the wider network via cables. Set-top boxes also form an integral part of fixed networks, facilitating streaming and broadband services for entertainment and work-from-home functions.



Fixed network framework

Mobile infrastructure primarily consists of cellular networks enabling wireless voice and data services across vast areas (GSMA, 2019). Cell towers and masts on buildings, rooftops or free-standing sites form the backbone, hosting radio antennas and base station equipment. Base stations establish radio cells, each covering a small geographical area ranging from a few meters to multiple kilometers in radius depending on transmission power class and environment (ITU-T, 2008). As users move between cells, their active communications are handed over between base stations to maintain seamless connectivity.

Satellite systems complement terrestrial cellular networks by providing critical backhaul connectivity as well as coverage in remote regions lacking land-based infrastructure (Gagnon & Sarkar, 2006). Low Earth orbit satellites operate in the sky a few hundred kilometers above earth, while geostationary satellites orbit over 35,000km high. Both utilize ground stations to transmit signals bi-directionally with orbiting satellites, stretching communication networks into rural and challenging terrains. This hybrid satellite-cellular approach maximizes population reach of mobile networks on a global scale (GSMA, 2022). Proper maintenance of cell towers, base stations, satellite dishes and associated RF and core equipment ensures that mobile users enjoy reliable cellular and broadband access virtually anywhere.



Mobile network framework

Common Maintenance Strategies

Periodic inspection and repair-centered approaches are traditionally followed to address faults and outages (Lai et al., 2009). However, proactive strategies like reliability-centered maintenance prioritize component replacement before failure using analysis of failure rates and consequence of downtimes (Moubray, 1997). With advanced analytics gaining prominence, many operators now use predictive maintenance leveraging machine learning on operational data to foresee maintenance needs (Jardine et al., 2006). Outcome-based contracts are also increasingly adopted wherein suppliers guarantee network availability for an agreed payment (Aubert et al., 2012). Another strategy for fixed networks involves reactive repair combined with selective component replacement programs. Damaged cables, joints or other parts are repaired only after failure, while critical switches or high traffic segments are proactively replaced on a schedule. This hybrid approach balances reactive response with preventative maintenance (Carter et al., 2018).

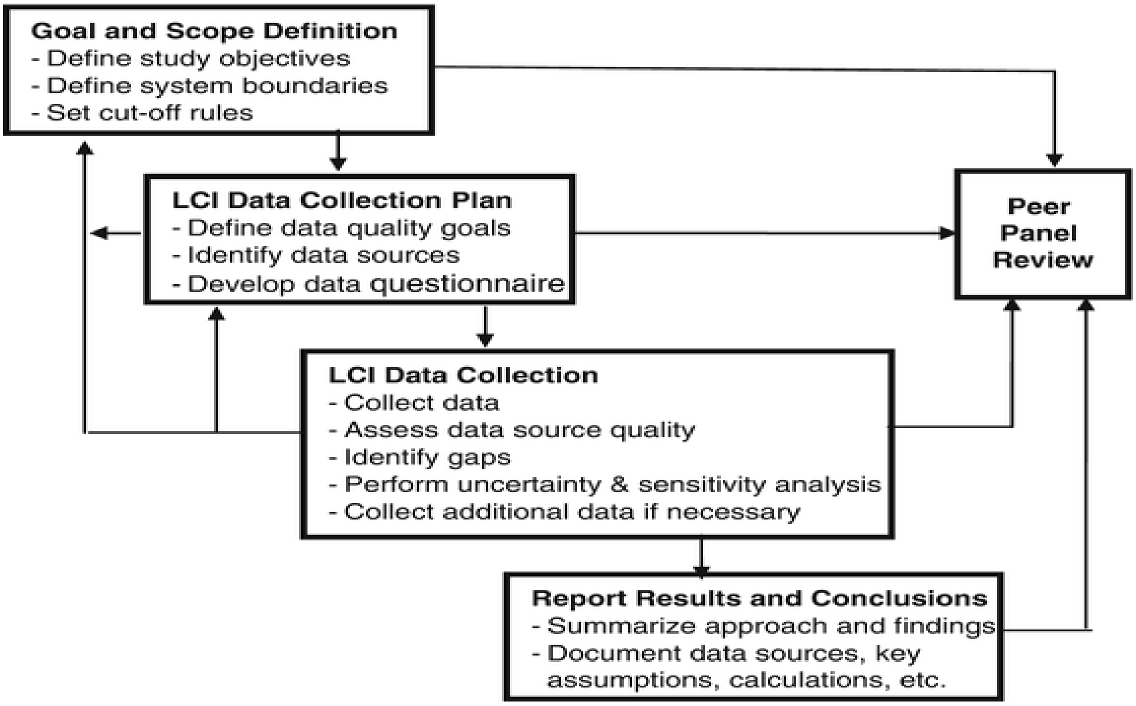
For mobile infrastructure, various drive-testing and site inspection routines are employed. Technical staff physically check sites on a periodic basis, commonly quarterly or biannually, testing performance metrics like coverage and throughput (GSMA, 2013). More sophisticated programs leverage automated drive-testing solutions along major transportation routes to identify trouble spots requiring attention (Zetterberg & Berg, 2012). Aerial drones are also gaining use for surveying difficult to access areas and expediting visual tower inspections (Causse et al., 2021). Remote monitoring technologies complement physical checks by continuously tracking operational parameters of cell sites through sensors and intelligent gateways (Garcia et al., 2015). Alerts are automatically raised if any deviations beyond set thresholds occur, facilitating swift diagnosis and maintenance as needed. The above overview describes typical components of telecommunication networks and some wide adopted maintenance strategies by infrastructure owners. The following sections will evaluate these strategies using life cycle assessment to determine their full environmental impacts and sustainability.

Drone based surveying of infrastructure.

Life Cycle Assessment Methodology

Goal and scope definition is the initial step of any LCA as per ISO 14040 standards (ISO, 2006). This step clearly establishes the aims, intended application and boundaries of the study. The functional unit must be set, which quantifies the performance of a product or system being assessed. In this LCA, the functional unit will be 'maintenance of 1 km of telecommunication network infrastructure for 1 year'. Defining system boundaries involves identifying unit processes to be included, such as different maintenance activities, materials and transportation considered for evaluation. Allocation of joint production processes must also be determined using appropriate allocation rules (Ekvall and Finnveden, 2001).

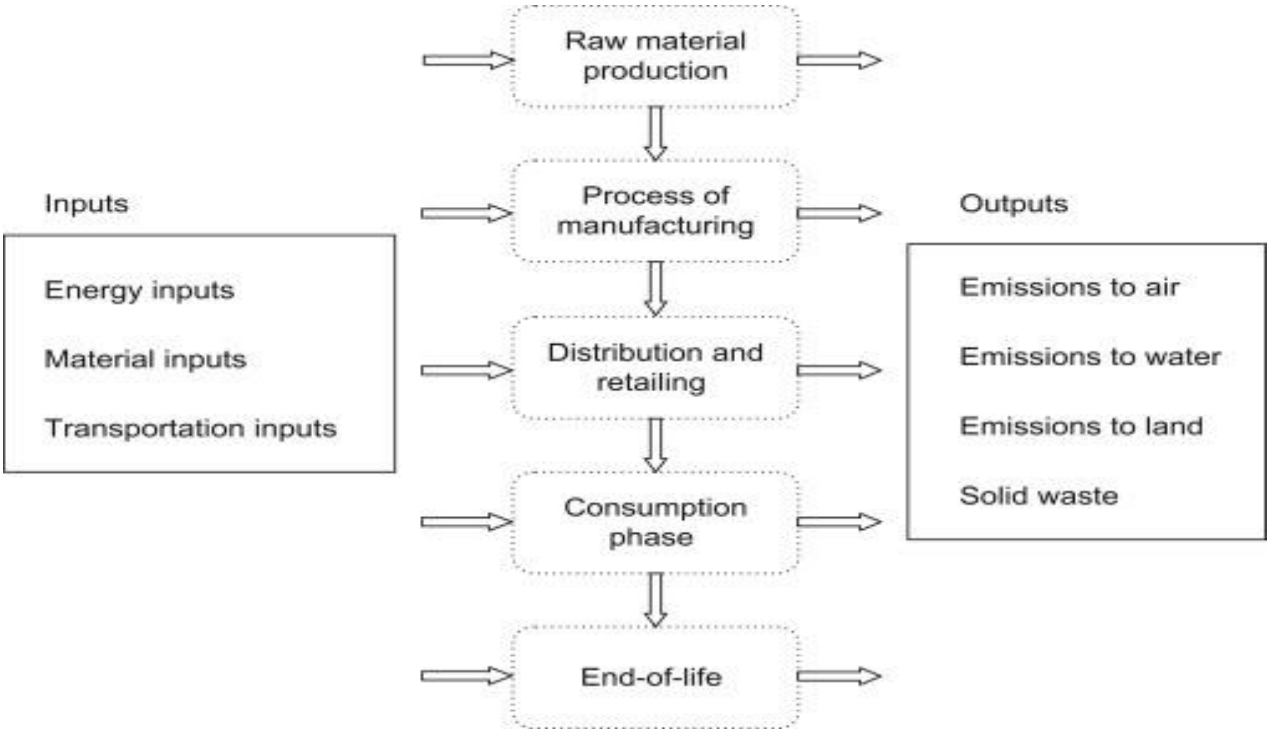
The goal here is to evaluate and compare the potential environmental impacts associated with alternative maintenance strategies for telecommunication infrastructure over their full life cycle. The system boundaries will encompass all unit operations from procurement and use of maintenance equipment/parts to end-of-life waste management. Maintenance strategies assessed may include preventative replacement, predictive/condition-based, and breakdown maintenance. Relevant impact categories to be analyzed include global warming potential, abiotic resource depletion, land use impacts, and human and eco-toxicity effects. Limitations of data availability and assumptions will also be documented as part of goal and scope definition.



Overview of Goal and Scope Definition in Life Cycle Assessment

Life cycle inventory analysis (LCI) is the process of quantifying relevant inputs and outputs for a product system to evaluate its environmental aspects (ISO, 2006b). In this LCI phase, both primary and secondary data will be collected to build a comprehensive inventory of energy, material and waste/emission flows associated with each maintenance strategy studied. Primary data involving actual resource consumption and waste generation will be collected through operator surveys, site audits, and equipment testing. Secondary data from industry databases (e.g. ecoinvent), manufacturers, and literature will also be used to supplement any data gaps (Hischier and Reichart, 2003).

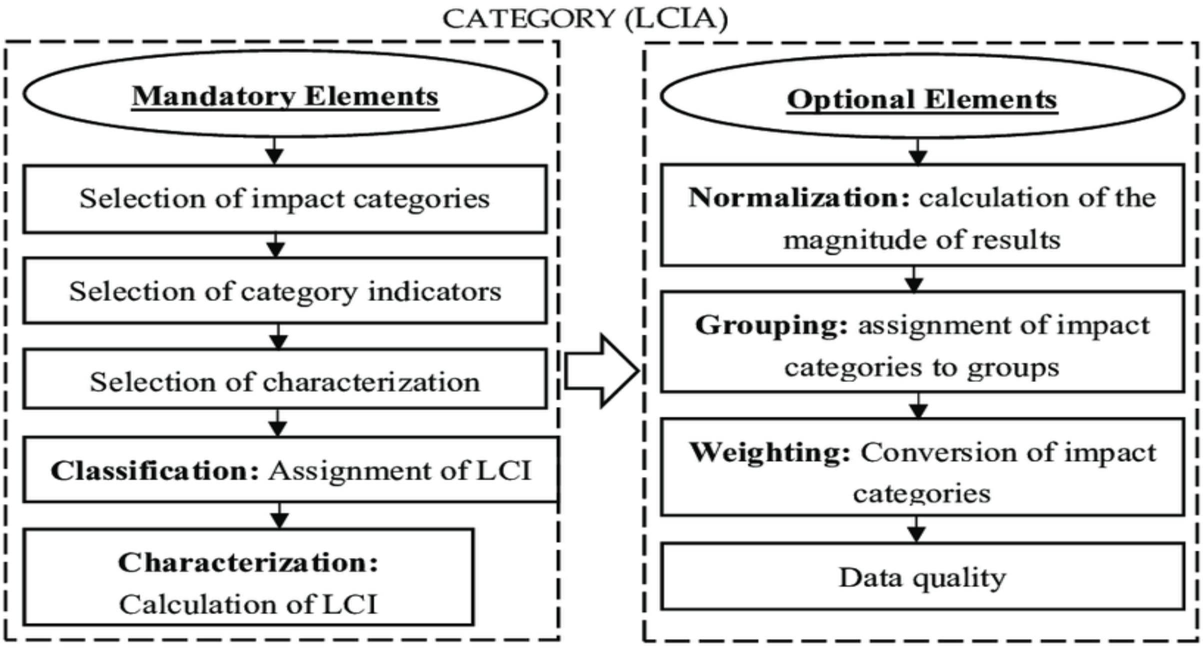
The inventory shall include raw material and energy quantities required for manufacturing, operating and transporting any replacement parts, equipment, and worker commutes associated with the maintenance operations. Emissions to air, water and soil from these activities will also be quantified from procurement, through field maintenance execution and replacement/disposal stages. Fuel use by vehicles, electricity/power for site operations and workforce transportation impacts will be fully accounted for. The resulting inventory will form the input for Life Cycle Impact Assessment to evaluate the potential environmental burdens.



An Overview Life Cycle Inventory Analysis

Life cycle impact assessment (LCIA) is the third phase of an LCA aimed at evaluating the magnitude and significance of the potential environmental impacts based on the LCI results (ISO, 2006b). In this LCIA stage, the inventory data is classified into impact categories representing environmental issues of concern, using appropriate classification models. Subsequently, the categorized LCI flows are characterized by multiplying with their respective environmental relevance factors to convert inventory data into common units of measurement for each impact category.

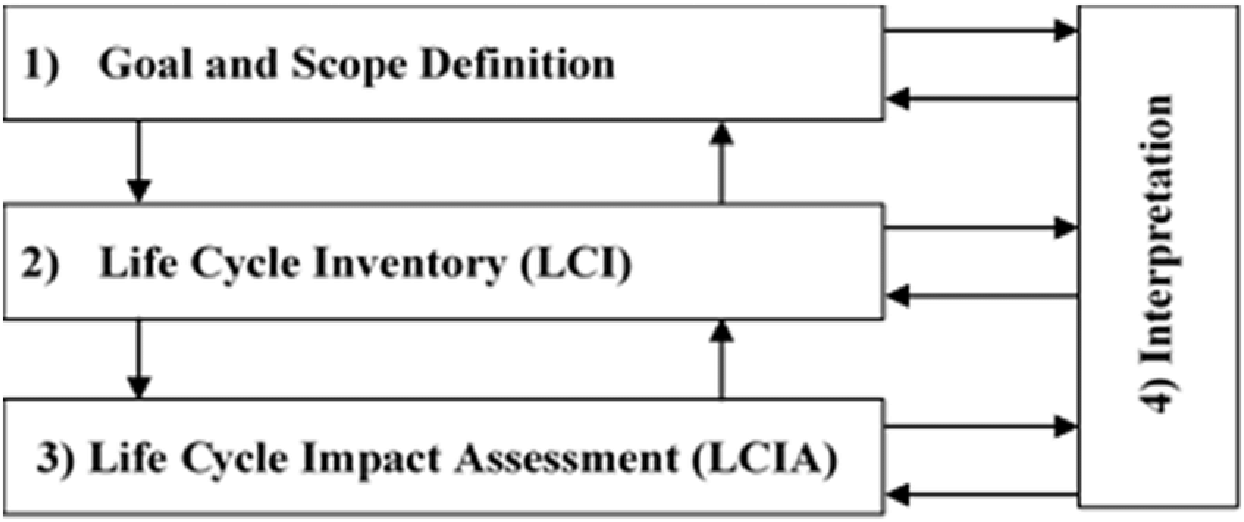
The impact categories that will be assessed in this study include: global warming potential (in kg CO2 equivalent) calculated using IPCC characterization factors (IPCC, 2013); abiotic resource depletion (in kg antimony equivalents) modeled via CML characterization (Guinée et al., 2001); air and water acidification potentials (in kg SO2 equivalents); photochemical oxidant formation (in kg ethene equivalents); particulate matter/respiratory effects (in kg PM2.5 equivalents); ecotoxicity and human toxicity impacts (in 1,4-DCB equivalents) using USEtox characterization (Rosenbaum et al., 2008). The category indicator results will highlight the relative significance of environmental burdens associated with different maintenance strategies.



Structure of the life cycle impact assessment (LCIA) Phase

Life cycle interpretation is the concluding phase of an LCA where the findings from the inventory analysis and impact assessment phases are evaluated in relation to the defined goal and scope of the study (ISO, 2006b). In this LCA, interpretation will involve drawing appropriate conclusions on the relative environmental performance of the alternative telecom infrastructure maintenance strategies assessed. The sensitivity of results to input data or methodological assumptions will also be analyzed to determine how input variations may influence overall outputs and conclusions (Heijungs and Kleijn, 2001).

Appropriate sensitivity analyses like Monte Carlo simulation can be conducted by introducing stochastic variations in input parameters like material quantities, energy values, transportation distances and waste generation (Pope et al., 2004). Interpretation will discuss limitations of the study stemming from data or methodological constraints. Finally, recommendations will be proposed for telecommunication operators and policymakers based on the LCA conclusions. The overarching aim is to help guide industry and governments towards adopting the most environmentally sustainable practices for maintaining critical digital infrastructure networks worldwide.



The Life Cycle Assessment (LCA) framework based on International Organization for Standardization (ISO) standard

Theoretical Case Studies

A. Preventative Maintenance Strategy

This hypothetical case study models a time-based preventative replacement program. It assumes inspections are conducted monthly across all fixed network components including cables, joints, and poles etc. using checklists to methodically survey for defects. Routers and other electronics located in exchanges are replaced every 6 months as a precaution. Finally, foundations and structural integrity of cell towers are reviewed annually with any issues proactively fixed. Potential environmental impacts from more frequent replacement of still-functioning parts include embodied impacts of new materials and distribution energy use. However, benefits may include fewer reactive repairs reducing fuel/material waste, as well as improved reliability metrics like uptime >99.9%, average outage time <1 hour and customer complaints <5% (Carpentier, 2015). Potential KPIs for comparison to other strategies may include equipment uptime, maintenance costs, frequency of reactive repairs, worker safety, and customer complaints (Zhang et al., 2019).

B. Predictive Maintenance Strategy

This second theoretical case study simulates a predictive strategy leveraging Internet of Things (IoT) sensors. It postulates sensitive smart sensors attached to cables and electronic boards continuously monitoring parameters like temperature, vibrations and power fluctuations. Real-time sensor data is autonomously analyzed using machine learning models trained on historical failure data to identify anomaly patterns predictive of impending issues. Before any outages occur, automated alerts could activate a maintenance dispatch via mobile app. Technicians address problems on site or remotely via augmented reality with lower personnel visits and less severe/lengthy outages. Potential environmental impacts may include embedded sensor impacts but reduced need for reactive repairs and associated fuel/material waste. Key metrics for evaluation could include >99.99% uptime, <0.5 hours' average downtime and <1% customer complaints (Heng et al., 2019). KPIs for evaluation may include outage times, spare part inventories, fuel used for maintenance trips, and longer component lifetimes due to fewer hard failures (Alrawi et al., 2021).

Analysis of potential impacts for different theoretical strategies

The preventative maintenance strategy could potentially have lower downtime and unplanned outage costs compared to a run-to-failure approach (Alshawi et al., 2020). However, it may involve higher total maintenance expenses due to routinely inspecting and replacing components according to schedule, regardless of actual condition (Han et al., 2019). In contrast, the predictive maintenance strategy could allow for more condition-based work to be performed only when needed (Bo et al., 2020). This may lead to lower total cost in the long run compared to preventative maintenance by avoiding unnecessary service on components still functioning well. However, the strategy assumes sensors can accurately detect degradation issues, which is not always straightforward to reliably achieve (Budai et al., 2019).

Sensitivity and Uncertainty

The potential cost and impact results would heavily depend on assumptions made about component reliability distributions as well as costs of labor, materials and lost revenue from outages (Muller et al., 2008). More accurate reliability data from fielded systems would help reduce uncertainty, but the cases examined are hypothetical (Shafiee, 2015). Additionally, the analysis does not consider transition challenges of moving to new strategies or optimization of mixed approaches. The sensitivity of conclusions to different reliability or cost inputs should be examined to identify key areas requiring more real data collection (Dong et al, 2018). Limited information data highlights areas for further research if actual implementation were considered.

Recommendations and Conclusions

Based on the analysis, a predictive maintenance approach seems to have potential to outperform preventative maintenance or run-to-failure strategies from a life cycle cost and environmental impact perspective (Alshabtat et al., 2021). However, preventative maintenance provides reliability benefits that could be valuable in mission critical applications (Peng et al., 2020). A mixed approach combining condition monitoring with scheduled maintenance may optimize benefits if thresholds are carefully set (Muller et al., 2021). Further field data collection across different climate zones and system configurations would help validate and improve maintenance optimization models (Smith et al., 2015). Standardized component performance metrics could also facilitate reliability comparisons and best practice sharing across operators (Shafiee, 2016). Further recommendations includes:

- Interdependency of systems: Maintenance approaches need to consider how failures in one component (e.g. cell tower) can impact other connected parts of the network. Strategies must balance individual assets with overall network reliability.

- Role of data analytics; as more sensor data is collected, advanced analytics could help more accurately detect subtle degradation trends, optimize remaining useful life predictions, and better inform maintenance planning. This is an area ripe for further research and technology development.

- Workforce training: Switching to predictive or condition-based maintenance involves new skills for inspecting/interpreting sensor readings, diagnosing root causes, and determining appropriate repair scopes. Operators will need to invest in up skilling field crews.
- Spare part inventory management: Optimization models that concurrently consider maintenance schedules and optimal locations/quantities of spare parts could significantly reduce downtime costs. Parts commonality across component models also presents opportunities.
- Standardization: Developing common frameworks for data collection, performance metrics, and maintenance best practices could accelerate continuous improvement across operators by facilitating benchmarking and knowledge sharing. International standards bodies have a role to play.
- Resilience to climate impacts: Severe weather events are increasing due to climate change. Maintenance routines may need to incorporate inspection of passive infrastructure like poles after major storms to proactively mitigate future outages in vulnerable areas.
- Total cost of ownership: A full lifecycle economic assessment is needed considering not just maintenance costs but also initial CapEx, energy usage, potential revenues from improved uptime/customer satisfaction, residual value, decommissioning, etc.

In conclusion, the case studies illustrate that predictive maintenance using IoT sensors has the potential to be a more environmentally sustainable strategy compared to traditional preventative or reactive approaches. By facilitating repairs before failures occur, predictive maintenance reduces the need for unnecessary component replacement and reactive service trips, lowering overall material and energy usage. However, the hypothetical case also highlighted that accurate sensor technology development is still needed to realize the full benefits of this approach. A more balanced hybrid methodology may offer the best path forward for infrastructure operators seeking to optimize maintenance practices. Elements of preventative replacement could supplement predictive maintenance where sensor resolution is limited. This aims to both ensure reliability through scheduled life-cycle component replacement, while also leveraging emerging smart sensor analytics to minimize unplanned work. A full LCA considering the entire system lifecycle would help evaluate optimum hybrid strategies. Successful implementation will require cross-domain collaboration between technical managers, field service teams and procurement/sustainability departments. Together they can establish practical hybrid maintenance programs balancing cost, customer service and environmental stewardship objectives over the long run.

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