Evaluating Cable Network Inventory Methods

Long-Term Scenarios

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1. Introduction

Accurate cable network inventory information, including device configurations and network topology data, is crucial for the efficient operation and management of modern telecommunication networks. This data impacts customer experience, service reliability, telemetry, operational efficiency, cost management, cyber security, future readiness, and innovation. These implication areas are illustrated in Figure 1.

Discrepancies in inventory data can lead to service outages and negatively impact customer satisfaction, resulting in revenue loss (Torrente et al., 2021). Reliable inventories ensure that service changes and network upgrades are based on accurate data, reducing interruptions and enhancing customer satisfaction.

Network operators must optimize their capital investments by managing inventory and configuration information accurately, comprehensively, and cost-effectively. While collecting data about physical network assets may seem straightforward, the dynamic nature of today's networks complicates this task. Consequently, inaccurate and incomplete records of inventory and configuration data hinder operators from optimizing their networks (Sundelin, 2017; Torrente et al., 2021).

Maintaining an accurate cable network inventory can significantly enhance operational efficiency and reduce costs. Sundelin (2017) highlights that virtualization and the introduction of software-defined networking (SDN) add complexity to network management, necessitating sophisticated assurance capabilities that encompass both physical and virtual resources in real-time. Effective inventory management supports these capabilities by providing up-to-date information on network assets, facilitating better resource allocation, and minimizing redundant expenditures. Similarly, Torrente et al. (2021) discuss the inefficiencies and costs associated with discrepancies between network inventories and the actual state of the network.

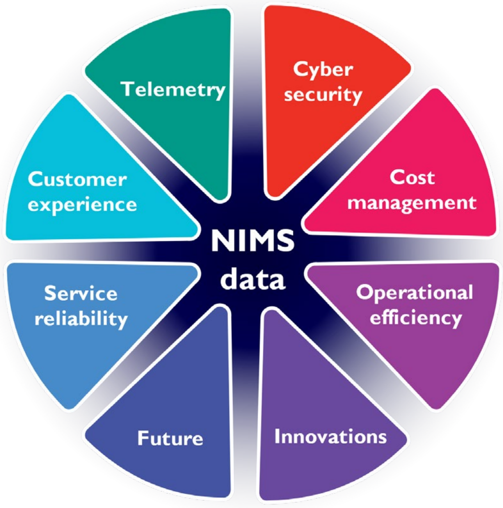

Figure 1 - Implication Areas of Accurate NIMS Data

Recent studies emphasize the importance of meticulous data management, including inventory data, in driving operational processes and innovation. Accurate inventories ensure that data-driven strategies can be effectively implemented, supporting both current operations and future innovations (Castro et al., 2020), thereby keeping network technologies relevant. This aligns with findings that reliable inventory management is crucial for maintaining rapid real-time responses. Eiden et al. (2021) further underscore the importance of inventory management as part of broader risk management and resilience strategies. An accurate inventory helps organizations quickly identify and address vulnerabilities, maintaining service reliability and protecting customer data. Precise network inventory can also facilitate the operation of telemetry technology, which is expected to become the standard mechanism for efficiently collecting operational data from network devices.

The evolution of cable networks, including the adoption of extended spectrum hybrid fiber-coaxial (HFC) systems, underscores the need for accurate inventory management. As networks evolve, maintaining accurate inventories is essential for seamlessly integrating new technologies and optimizing their performance (Segura, 2021; Segura & Sandino, 2021). Moreover, applying machine learning (ML) and predictive maintenance techniques in network management highlights the importance of accurate inventory data. ML algorithms rely on precise data to predict potential failures and optimize maintenance schedules, thus extending the lifespan of network components and reducing downtime (Volpe, 2021).

Given these significant impacts, our study evaluates three methods for maintaining and acquiring information from access networks—manual, semi-automatic, and automatic. Together with the network inventory database, these methods form the Network Inventory Management System (NIMS), which is crucial for the efficient operation and management of modern telecommunication networks. This includes not only assessing the extent of changes required in operational processes but also the effectiveness of these changes.

In the following chapters, we will delve into the specific data types stored in NIMS and discuss the three inventory and topology discovery methods in detail. We will then examine how these methods influence key variables critical to network performance and management. By analyzing these variables—technology relevance, data accuracy, real-time response, operational expenses (OPEX), capital expenses (CAPEX), and operational processes—we aim to provide a comprehensive framework for cable operators. This framework will enable more informed decision-making in selecting a suitable access network inventory and topology discovery method, ultimately enhancing overall network performance and reliability.

Our approach integrates systems theory principles to ensure a structured and holistic evaluation, considering the complex interplay of various factors affecting NIMS. This study highlights the importance of accurate network inventory management and provides actionable insights for optimizing network operations in an increasingly dynamic and technology-driven landscape.

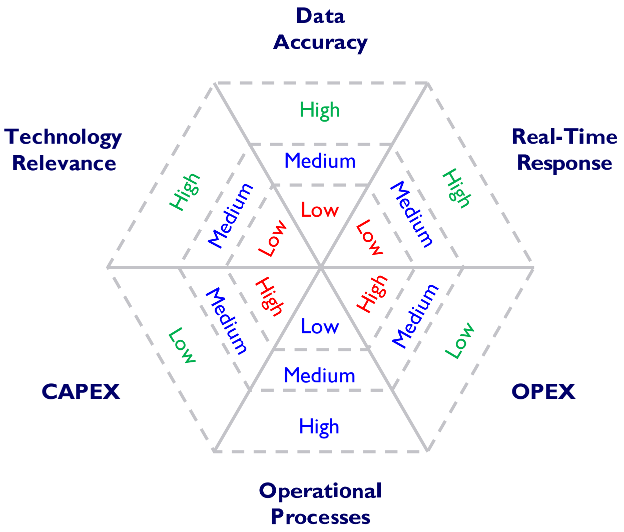

Figure 2 - Studied Variables

2. Connecting Selected Variables to Key Operational Implications

In this chapter, we elucidate the rationale behind selecting six key variables for our study: technology relevance, data accuracy, real-time response, OPEX, CAPEX, and operational processes. We demonstrate how these variables directly impact crucial operational areas such as customer experience, service reliability, telemetry, operational efficiency, cost management, cyber security, future readiness of networks, and innovations. While we focus on the top three variables for each operational area, it is important to note that other variables may also be connected indirectly as moderators, influencing these areas through complex and multifaceted relationships.

2.1. Technology Relevance

Definition: Evaluating the ability of each method to remain effective and relevant as network demands evolve and new technologies (e.g. ML & AI) emerge.

Top Operational Areas:

Service Reliability: Keeping the network updated with the latest technology helps maintain consistent and reliable services, reducing the risk of outages and performance degradation.

Cyber Security: Adopting the latest technologies enhances cybersecurity measures, protecting the network from emerging threats.

Future Readiness of Networks: Ensuring the network can integrate future technologies is essential for long-term sustainability and growth.

2.2. Data Accuracy

Definition: Assessing the long-term reliability and accuracy of each method in preserving data integrity amidst network modifications and upgrades.

Top Operational Areas:

Customer Experience: Accurate data ensures customers receive reliable services without interruptions caused by data errors, enhancing customer satisfaction.

Service Reliability: Reliable inventory data is crucial for maintaining consistent network performance and preventing service disruptions.

Telemetry: Effective telemetry relies on accurate data to monitor and manage the network proactively, enabling timely interventions and maintenance.

2.3. Real-Time Response

Definition: Examining how each method supports real-time network monitoring and rapid response capabilities over time.

Top Operational Areas:

Customer Experience: Quick resolution of network issues enhances customer satisfaction by minimizing downtime and service disruptions.

Service Reliability: Real-time monitoring and response capabilities help maintain consistent and reliable network services, reducing the impact of faults and failures.

Operational Efficiency: Faster response times improve overall efficiency by reducing the time and resources needed to address network problems.

2.4. Operational Expenses (OPEX)

Definition: Investigating changes in operational expenditures over time for each method.

Top Operational Areas:

Operational Efficiency: Reducing operational expenses improves overall efficiency by freeing up resources for other critical tasks and investments.

Cost Management: Keeping operational costs under control is crucial for the financial health and sustainability of the network.

Service Reliability: Efficient use of resources ensures consistent and reliable network services, reducing the risk of service disruptions due to budget constraints.

2.5. Capital Expenses (CAPEX)

Definition: Evaluating the capital expenditures required for each method.

Top Operational Areas:

Cost Management: Effective management of capital expenditures ensures sustainable investment in network infrastructure, balancing short-term costs with long-term benefits.

Future Readiness of Networks: Investing in future-proof technologies ensures the network can adapt to evolving demands and remain competitive.

Innovations: Strategic capital investments enable the adoption of innovative technologies and solutions, driving network improvements and advancements.

2.6. Operational Processes

Definition: Assessing the extent to which operators must (1) adapt their operational processes over time due to the selected method and (2) the subsequent improvements these changes bring to those processes.

Top Operational Areas:

Operational Efficiency: Streamlined processes contribute to higher efficiency by reducing the time and effort required to manage the network. The changes introduced should enhance overall operational efficiency.

Service Reliability: Effective processes ensure consistent and reliable network operations, minimizing the risk of service disruptions. Process changes should improve the reliability of service delivery.

Customer Experience: Efficient operational processes lead to quicker resolutions of customer issues, enhancing overall satisfaction. The improvements in processes should positively impact customer experience.

2.7. Summary

By selecting these six variables, our study aims to provide a comprehensive evaluation of different network inventory management methods and their impact on critical operational areas. Understanding the connections between these variables and key operational implications allows network operators to make informed decisions, optimize their network management practices, and enhance overall performance and reliability. Table 1 illustrates the variables and their impact on eight crucial operational areas.

Table 1 – Variables and Implications

	customer experience	service reliability	telemetry	operational efficiency	cost management	cyber security	future readiness of networks	innovations
Technology Relevance		X				X	X	
Data Accuracy	X	X	X					
Real-Time Response	X	X		X				
OPEX		X		X	X			
CAPEX					X		X	X
Operational Processes	X	X		X				

3. NIMS and Methods

First, we define the Network Inventory Management System (NIMS) by discussing the types of data it stores about the access network. Afterward, we focus on what we mean by manual, semi-automatic, and automatic methods.

3.1. Stored Data

Our paper focuses on the access network, defined as the network starting from distributed access architecture (DAA) devices, often remote PHY devices (RPDs), and ending before customer premises. Thus, cable modems (CMs) are not part of the access network in our study. In our paper, the NIMS is primarily a repository and management interface that collects, stores, analyzes, and presents data about the network's (1) components, (2) their configurations, (3) telemetry, and (4) documentation. In real-life implementations, the NIMS can consist of several subsystems, and for example, monitoring of the network can be managed with other systems not called NIMS by the industry.

Component data:

- Device identifiers (e.g., serial number), device type identifiers (e.g., trunk amplifier)
- Location details (coordinates)

Configuration data:

- Configurations of all operational devices (mainly active devices) and parameters (mainly passives)
- Network topology information

Telemetry data:

- Bandwidth usage, error rates, alarms, temperature, uptime, change management logs

Documentation:

- Network diagrams, rack diagrams, user manuals, operational guidelines

3.2. Manual, Semi-Automatic, and Automatic Methods

A summary of these methods is described in Table 2, which cross-tabulates the content of section 3.1 with the methods described below. In all descriptions, we focus on the capabilities of amplifiers as DAA devices always have interfaces for remote connection.

3.2.1. Manual Method:

In the manual method, the data described in section 3.1 is maintained manually in the NIMS. After networks are designed and implemented, all changes to the network are documented in written format, whether digital or non-digital. NIMS can still contain exact and correct data, including network topology information, but operators and network technicians must follow rigorous processes to maintain the data stored in the NIMS repository. This method relies heavily on human input.

3.2.2. *Semi-Automatic Method:*

In the semi-automatic method, the data described in section 3.1 can be uploaded to the NIMS repository via a temporary mobile connection that requires field technicians to physically visit device locations. When on-site, the technician can connect a mobile device (wirelessly or through a wired connection) to the active device supporting this approach. This typically occurs when a device is installed, repaired, or its configuration is changed. Although this approach requires field technicians to follow strict processes, the information in NIMS is less prone to human errors compared to the manual method. However, data is less real-time than with the automatic method. The use of remotely operated wink switches, which allow attenuators in amplifiers to be operated remotely and their impact on the signal observed via upstream received by DAA devices, is classified as a semi-automatic method. While laborious, this method allows for remote identification of network topology. However, it cannot be used to read telemetry data remotely, which requires a more automated approach.

Table 2 - Cross-Tabulation of Data Categories and Methods within the NIMS Framework

	Manual Method	Semi-automatic Method	Automatic Method
Connectivity Technology	Not available	Temporary mobile connection + unidirectional receivers in amps	Always-on transponder connection
Topology Discovery Technology	Manual	Wink switches	Transponders and algorithms
Components and Configurations	The data described in section 3.1 is maintained manually in the NIMS. However, DAA devices are an exception.	NIMS updated either manually or semi-automatically when technicians are visiting sites. Limited network topology discovery via wink switches is possible.	NIMS always updated regarding devices capable of producing data. NIMS has always updated network topology information.
Telemetry	Not possible besides DAA devices.	Limited availability when technicians are visiting sites or controlling ingress remotely.	All information available real-time.
Documentation	Maintained and used manually.	Advanced field devices can be used to store user manuals and operational guidelines for technicians who can access them when needed.	

3.2.3. *Automatic Method:*

In the automatic method, all amplifiers are equipped with transponders, either as plug-in modules or natively integrated into the amplifiers. These amplifiers can produce real-time data, including information about components, their configurations, and telemetry. This approach minimizes human intervention, reduces errors, and enhances the timeliness and accuracy of the data in NIMS.

4. Systems Theory and The Network Inventory Management System

We utilize systems theory, as articulated by key figures such as Ludwig von Bertalanffy (1968) and W. Ross Ashby (1956), to enhance the robustness of our paper and framework. Systems theory is widely applied across various disciplines, including biology, ecology, engineering, and organizational studies, to understand and analyze complex systems. While the foundational work on systems theory was established decades ago, these theories have continued to evolve and remain highly relevant today (Mele et al., 2010). Systems theory is widely applied in modern contexts such as sustainability studies, cybersecurity, and artificial intelligence (AI). For example, Mitchell (2009) explores the application of systems theory in understanding complex adaptive systems, including AI and ML. These contemporary applications underscore the enduring impact and versatility of systems theory. By using systems theory as a lens, we can provide a structured and holistic approach to understanding the NIMS.

4.1. Systems Theory

Systems theory offers widely tested foundational premises, which we have grouped into four distinct categories: (1) System Dynamics, (2) Complex Systems, (3) Regulation and Feedback Mechanisms, and (4) Adaptive Systems. These categories serve as the theoretical underpinning for analyzing the NIMS framework and are essential for understanding and managing its complexities.

System Dynamics

System Dynamics emphasizes the interdependence of parts within a system and the interactions between subsystems. This concept is crucial for understanding how changes in one part of the system can affect the entire network. For NIMS, this means recognizing the interconnectedness of different network components and the necessity of integrating manual, semi-automatic, and automatic methods cohesively. Effective NIMS should dynamically adapt to changes in the network, ensuring seamless interaction and data flow between components.

> For instance, when a new device is added to the network, the automatic method can immediately integrate this device into the system and update NIMS data, which is more challenging with manual methods.

Complex Systems Understanding

This category highlights the importance of viewing systems holistically rather than as a collection of parts. It recognizes that complex behaviors can emerge from simple interactions among the components of the system. For NIMS, this involves managing inventory data effectively across different network segments and understanding how simple data entries can lead to complex network behaviors. A holistic approach ensures that NIMS can manage the complexity of the network, allowing for comprehensive data analysis and optimization of network performance.

> For example, minor changes in the configuration of a single amplifier in a large network could have significant impacts on the other amplifiers in the same cascade, which the automatic method can monitor and adjust for in real-time.

Regulation and Feedback Mechanisms

This category focuses on the self-regulating nature of systems through feedback loops and the maintenance of system boundaries. NIMS should be designed with self-regulating mechanisms to maintain a balanced and accurate representation of network inventory and topology. This means that

NIMS should continuously update and adjust based on real-time data and feedback from the network, ensuring stability and accuracy without requiring constant manual intervention.

> For example, if an amplifier starts showing signs of potential failure, the automatic method can detect these signs through telemetry data and trigger preemptive maintenance actions, reducing downtime and improving service reliability.

Adaptive Systems

Adaptive Systems underline the importance of flexibility and responsiveness for system survival. NIMS must be capable of accommodating technological advancements and changes in network infrastructure, ensuring that it remains relevant and effective. This involves the ability to integrate new technologies and adjust processes as the network evolves, maintaining efficiency and effectiveness over time.

> For instance, as new technologies like extended spectrum amplifiers (1.8 GHz) are adopted, the automatic method can seamlessly incorporate these technologies into the existing network inventory, ensuring continuous and optimized network performance.

4.2. Systems Theory and Analyzed Variables

The principles of system dynamics highlight the need for integrated methods within NIMS. Complex systems understanding underscores the importance of viewing the inventory system as a whole, while regulation and feedback mechanisms emphasize maintaining balance and continuous improvement. Finally, the ability to adapt ensures that NIMS remains relevant and effective amidst evolving network technologies.

As shown in Table 3, the six variables presented in the introduction are analyzed using the questions covering the four cohesive categories described above. Table 4 answers these questions from the perspective of the manual method, while Table 5 addresses the semi-automatic method, and Table 6 addresses the automatic method. In our analysis, we assume operators are currently using and familiar with the manual method. Transitioning to other methods would require unlearning old principles and adopting new ways to manage NIMS and the data stored within it.

Table 3 - Cross-Tabulation of Variables, Systems Theory Categories, and Questions

	System Dynamics	**Complex Systems**	**Regulation and Feedback Mechanisms**	**Adaptive Systems**
Technology Relevance	How does the chosen method integrate with existing network technologies and adapt to new advancements?			
Data Accuracy	How does the method ensure accurate data through interactions and feedback mechanisms?			
Real-Time Response	How does the method support efficient real-time network monitoring and response to changes?			
OPEX	How does the method impact operational expenses and ensure cost-effective management?			
CAPEX	How does the method manage capital expenditures and adapt to new technology investments?			
Operational Processes	How does the method impact existing operational processes and does it increase efficiency over time?			

The manual method, while traditional, plays a significant role in specific contexts. Table 4 outlines how the manual method performs concerning each variable, highlighting its strengths and limitations.

Table 4 - Cross-Tabulation of the Variables and the Manual Method

Variable	Manual Method
Technology Relevance	The manual method does not integrate well with evolving technologies due to its reliance on human input and static data updates.
Data Accuracy	Data accuracy is often compromised due to human error and the labor-intensive nature of manual updates.
Real-Time Response	The manual method offers low real-time response capabilities due to its reliance on periodic, manual data updates.
OPEX	The manual method incurs high operational expenses due to the need for extensive human labor and periodic manual updates.
CAPEX	The manual method has low initial capital expenditures, as it primarily relies on existing human resources and minimal technological investment.
Operational Processes	With the manual method being the current standard, operators are already familiar with these processes. Thus, there is no immediate need for adapting operational processes. However, these processes are labor-intensive and inefficient, requiring rigorous manual data entry and frequent updates to maintain accuracy. Their continuity is difficult to manage if existing personnel retire or leave for other reasons.

Our findings on the manual method align with the literature in several key areas:

Technology Relevance: The manual method's inability to integrate well with evolving technologies is consistent with Sundelin (2017) and Torrente et al. (2021), who discuss the challenges of integrating manual methods with modern network technologies.

Data Accuracy: Our observation that data accuracy is often compromised due to human error and the labor-intensive nature of manual updates is supported by Torrente et al. (2021), who note the inefficiencies and errors associated with manual data management.

Real-Time Response: The low real-time response capabilities of the manual method, due to its reliance on periodic manual data updates, are highlighted by Torrente et al. (2021), who discuss the limitations of manual methods in providing real-time data.

OPEX: The high operational expenses incurred by the manual method, due to the need for extensive human labor and periodic manual updates, align with Torrente et al. (2021), who discuss the high operational costs associated with labor-intensive processes.

CAPEX: The low initial capital expenditures for the manual method, which relies on existing human resources and minimal technological investment, are noted by Sundelin (2017), who mentions the lower capital costs of manual methods.

Operational Processes: The manual method's labor-intensive and inefficient processes, requiring rigorous manual data entry and frequent updates to maintain accuracy, align with Torrente et al. (2021), who discuss the inefficiencies and sustainability challenges of manual processes.

This comparative analysis reinforces the validity of our observations and highlights the consistency of our findings with existing literature.

The semi-automatic method blends human oversight with automated tools, aiming to balance accuracy with efficiency. In Table 5, we explore how this hybrid approach impacts the six key variables, offering a middle ground between manual and automatic methods.

Table 5 - Cross-tabulation of the variables and the Semi-automatic method

	Semi-Automatic Method
Technology Relevance	The semi-automatic method partially integrates with evolving technologies, as it requires physical presence but allows for some degree of remote diagnostics and automation.
Data Accuracy	Data accuracy is improved compared to the manual method but still subject to errors because of partly physical data collection.
Real-Time Response	The semi-automatic method provides a medium level of real-time response, as it allows for limited remote diagnostics but still requires physical presence for configuration changes.
OPEX	The semi-automatic method has medium operational expenses, as it reduces some labor costs but still requires significant human involvement for data collection and updates.
CAPEX	The semi-automatic method requires moderate capital expenditures for mobile devices and connectivity solutions in the amplifiers to facilitate mobile data uploads.
Operational Processes	The semi-automatic method requires moderate adjustments to operational processes, as it introduces mobile configuration uploads but still relies on physical presence.

Our findings on the semi-automatic method align with the literature in several key areas:

Technology Relevance: The semi-automatic method's partial integration with evolving technologies aligns with general discussions on network management adaptability by Eiden et al. (2021) and Castro et al. (2020).

Data Accuracy: The improvement in data accuracy over the manual method, yet still being subject to errors due to physical data collection, is supported by discussions on error reduction in network management processes by Eiden et al. (2021).

Real-Time Response: The medium level of real-time response provided by the semi-automatic method, allowing for limited remote diagnostics, aligns with general discussions on real-time capabilities in network systems by Castro et al. (2020).

OPEX: The medium operational expenses of the semi-automatic method, which reduce some labor costs but still require significant human involvement, align with general discussions on balancing operational costs in network management by Eiden et al. (2021).

CAPEX: The moderate capital expenditures required for mobile devices and connectivity solutions in the amplifiers align with discussions on the initial investment in technology for network management systems by Castro et al. (2020).

Operational Processes: The moderate adjustments to operational processes required by the semi-automatic method, which introduces mobile configuration uploads but still relies on physical presence, align with general discussions on the partial operational changes needed for improved efficiency in network management by Eiden et al. (2021).

The automatic method leverages advanced technologies to minimize human intervention and maximize real-time data accuracy. Table 6 provides an in-depth look at how the automatic method affects the key variables, emphasizing scalability and efficiency.

Table 6 - Cross-Tabulation of the Variables and the Automatic Method

	Automatic Method
Technology Relevance	The automatic method fully integrates with evolving technologies, utilizing real-time data updates and advanced algorithms to ensure continuous adaptation and integration of new technologies.
Data Accuracy	Data accuracy is maximized through automated, real-time data collection and updates, minimizing human error and ensuring high reliability.
Real-Time Response	The automatic method offers high real-time response capabilities, enabling continuous monitoring and immediate adjustments based on real-time data.
OPEX	The automatic method has the potential for the lowest operational expenses over time, as it minimizes human labor and leverages automated processes for data collection and updates.
CAPEX	The automatic method involves higher initial capital expenditures due to the need for advanced devices and transponders, but offers long-term savings and efficiency.
Operational Processes	The automatic method requires substantial initial changes to operational processes, but ultimately streamlines operations through automation and continuous real-time updates.

Our findings on the automatic method align with the literature in several key areas:

Technology Relevance: The automatic method's full integration with evolving technologies, utilizing real-time data updates and advanced algorithms, aligns with general discussions on the need for advanced methods in network management to keep up with technological advancements by Segura (2021), Segura & Sandino (2021), and Volpe (2021).

Data Accuracy: The maximization of data accuracy through automated, real-time data collection and updates, minimizing human error and ensuring high reliability, is supported by discussions on the benefits of automated data management processes in enhancing data accuracy by Segura (2021) and Volpe (2021).

Real-Time Response: The high real-time response capabilities of the automatic method, enabling continuous monitoring and immediate adjustments based on real-time data, align with general discussions on the importance of real-time data and automated responses in network management by Segura (2021).

OPEX: The potential for the lowest operational expenses over time with the automatic method, as it minimizes human labor and leverages automated processes for data collection and updates, aligns with discussions on the long-term cost benefits of automation in reducing operational expenses by Segura (2021) and Volpe (2021).

CAPEX: The higher initial capital expenditures for the automatic method due to the need for advanced devices and transponders, but offering long-term savings and efficiency, align with discussions on the initial investments required for advanced network management technologies and their long-term benefits by Segura (2021).

Operational Processes: The substantial initial changes to operational processes required by the automatic method, but ultimately streamlining operations through automation and continuous real-time updates, align with discussions on the need for significant operational adjustments initially, followed by increased efficiency and streamlined processes by Segura & Sandino (2021).

This comparative analysis reinforces the validity of our observations and highlights the consistency of our findings with existing literature.

4.3. Comparison of NIMS Methods

The analysis across different tables reveals distinct advantages and disadvantages for each method. The manual method's flexibility is contrasted by its scalability issues, while semi-automatic methods offer a balanced approach. Automatic methods stand out for their efficiency and accuracy but come with higher implementation costs. This comprehensive examination aids in understanding which method may best suit different network management needs. Table 7 compares the three methods, which is followed by an illustration in Figure 3. Then, we discuss how these statements align with the widely tested foundational premises of systems theory.

Table 7 - Comparison of NIMS Methods

	Manual	Semi-automatic	Automatic
Technology Relevance	While medium in the beginning, the relevance drops to low.	Medium initially and remains medium, with slight improvements as new tools are adopted.	High in the beginning and stays high.
Data Accuracy	High in the beginning but drops low when years pass.	High in the beginning but drops to medium when years pass.	High initially and remains high.
Real-Time Response	Low in the beginning and stays low.	Medium in the beginning and stays medium.	High in the beginning and stays high.
OPEX	High initially (laborious installations) and remains high (laborious maintenance).	Medium in the beginning and stays medium.	Low initially and continues to decrease as efficiencies are realized.
CAPEX	Low in the beginning and stays low.	Medium in the beginning but drops to low.	High in the beginning but drops low.
Operational Processes	Low initially but grows increasingly inefficient as network size and complexity increase.	Medium in the beginning but becomes more efficient as processes are partly automated.	High initially but becomes more efficient as processes are automated.

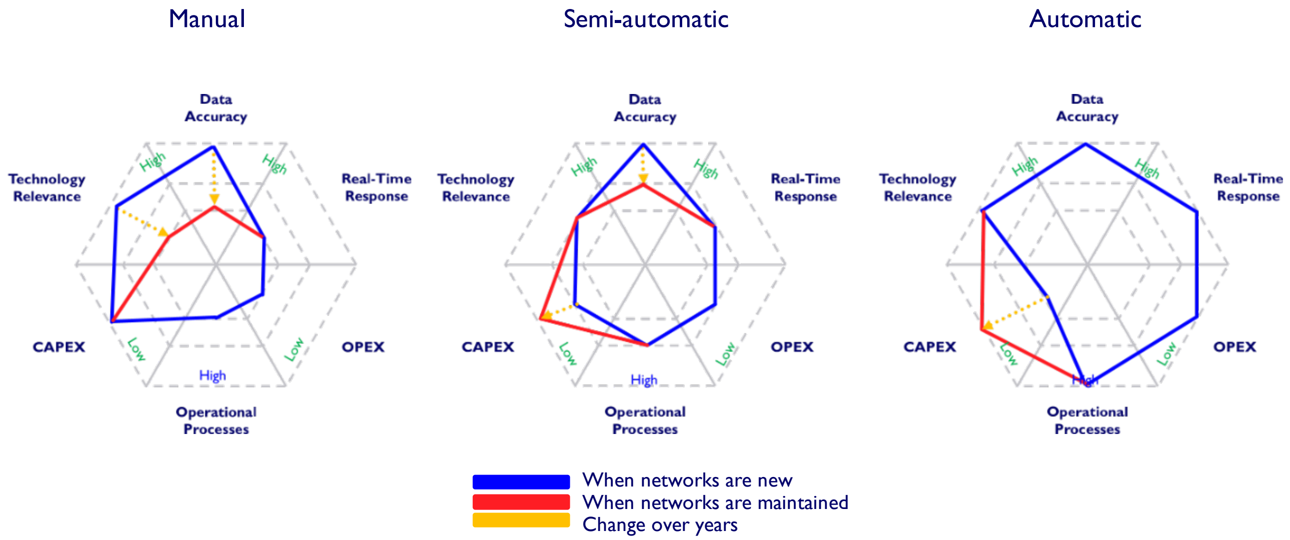

Figure 3 - Illustration of Variables per Method

4.4. Systems Theory Alignment

System Dynamics

Technology Relevance: The manual method's drop in technology relevance fails to maintain interconnectedness and integration, whereas the semi-automatic method partially adapts, and the automatic method exemplifies strong integration and continuous adaptation, fully supporting System Dynamics principles.

Operational Processes: The manual method does not introduce any changes to the current processes, making it easy to use initially but labor-intensive and inefficient, reflecting a lack of alignment with Adaptive Systems. The semi-automatic method introduces moderate changes, partially aligning with Adaptive Systems principles. In contrast, the automatic method necessitates substantial initial changes but ultimately streamlines operations through automation and continuous real-time updates.

Complex Systems

Real-Time Response: The manual method's low real-time response aligns with a lack of understanding of Complex Systems and an inability to dynamically interact with network changes. The semi-automatic method's medium response reflects some real-time interaction with limitations, while the automatic method's high real-time response supports efficient real-time monitoring and rapid response to network changes, aligning strongly with Complex Systems principles.

CAPEX: The manual method's low CAPEX aligns with Complex Systems, reflecting minimal investment in advanced technologies. The semi-automatic method's medium CAPEX aligns with a balanced approach to technology investment, while the automatic method's high initial CAPEX can be justified by the importance of investing in technologies that ensure long-term efficiency.

Regulation and Feedback Mechanisms

Data Accuracy: The manual method's decline in data accuracy over time reflects the lack of self-regulating mechanisms and feedback loops. The semi-automatic method shows improved but not optimal accuracy due to partial automation and reduced human error, while the automatic method maintains high data accuracy through real-time updates and automated feedback loops.

Operational Processes: The automatic method aligns well with Regulation and Feedback Mechanisms, as it supports significant adaptation and continuous improvement through automation and feedback loops.

Adaptive Systems

OPEX: The high OPEX of the manual method reflects inefficiency in resource allocation and labor-intensive processes, contrary to Adaptive Systems principles. The semi-automatic method balances costs, showing moderate alignment with System Dynamics, while the automatic method's low OPEX aligns with Adaptive Systems, ensuring efficient resource allocation and minimizing operational costs.

Technology Relevance: The integration and adaptation of evolving technologies are essential for maintaining system relevance, as demonstrated by the automatic method's high relevance, the semi-automatic method's medium relevance, and the manual method's declining relevance.

5. Conclusion

It might seem obvious that investing in NIMS provides cable operators with more accurate information regarding their network. However, our contribution lies not in merely supporting this statement but in the way we arrive at these conclusions. Our applied framework, the structured analysis, and the terminology we introduce for discussing the pros and cons of NIMS together with three alternative methods are the true contributions of this study. Our framework highlights how the integration of different NIMS methods can address the dynamic and interconnected nature of modern telecommunication networks. It emphasizes the importance of accurate data management across component, configuration, and telemetry data to enhance overall network performance.

One of the more counterintuitive insights from systems theory is the concept of nonlinearity. Our paper has largely focused on linear relationships between network management efforts and outcomes. However, we want to address the notion of nonlinearity to provoke further thought and discussion. Specifically, when the number of technicians increases linearly (the manual method), the number of human errors can also be expected to increase linearly. However, the consequences of those errors can escalate exponentially. This is because small inaccuracies can cascade into significant performance issues, highlighting the critical need for automated, real-time updates to effectively prevent these potentially nonlinear consequences.

In this study, we evaluated three methods for managing cable network inventory: manual, semi-automatic, and automatic. Together with the database where everything is stored, these methods form the Network Inventory Management System (NIMS), which is crucial for the efficient operation and management of modern telecommunication networks. We assessed these methods based on six key factors: technology relevance, data accuracy, real-time response, OPEX, CAPEX, and the impact on operational processes.

In practical terms, managing cable network inventory involves dealing with three types of data: component data, configuration data, and telemetry data. From these three types of data, future work should focus on telemetry, which seems to be an unexplored territory that could improve proactive maintenance and immediate response to potential issues.

While it is clear that the automatic method is superior in many aspects, each operator faces the challenge of balancing CAPEX and benefits. This balancing act requires quantifying the importance of elements that are extremely difficult to measure or assign weights to, such as technology relevance and data accuracy. To navigate these complexities, operators may find it helpful to agree on acceptable minimum levels for NIMS variables (technology relevance, data accuracy, real-time response, OPEX, operational processes) and determine which method meets these criteria.

Abbreviations

AI	artificial intelligence
CAPEX	capital expenditure
CM	cable modem
DAA	distributed access architecture
GHz	gigahertz
HFC	hybrid fiber-coaxial
ML	machine learning
NIMS	network inventory management system
OPEX	operational expenditure
RPD	remote PHY device
SDN	software-defined networking

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