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Multilayer Networks and Public Digital Health Scalability

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Abstract
Interoperable multilayer networks are not just tools but transformative solutions in public digital health. They enhance the delivery of healthcare services and significantly contribute to improving public health outcomes. By enabling better accessibility, efficiency, and data-driven decision-making, these networks are revolutionizing our approach to public health. Their seamless data exchange and integration across different healthcare systems and providers can lead to substantial cost savings for public healthcare systems. These networks are crucial in reducing redundancies and optimizing resource allocation, paving the way for a more efficient and effective healthcare system. This study combines the pressing issues of public digital health with the innovative interpretation of multilayer network theory, proposing practical solutions that inspire academics and practitioners alike.

Public digital health is instrumental in improving care access and patient engagement, ensuring the financial sustainability of our healthcare systems. The innovative multilayer network analysis is a game-changer in reducing spatial and temporal constraints. These networks are not just tools; they are solutions that streamline processes and improve efficiency by easing complex interactions within healthcare systems. This process, in turn, allows healthcare providers to deliver high-quality care at a lower cost, transforming, whenever possible, in-patients and out-patients into home-patients. The role of networks in improving care access and patient engagement is a cornerstone and a beacon of hope for transforming public digital health. They are increasing the Value for Money and enhancing a patient-centric approach, reassuring us about the future of healthcare.

This study shows that revolutionizing digital healthcare methodologies impacts crucial elements like resilience, interoperability, and patient well-being within public health. Enhancing interoperability facilitates the smooth flow of data exchange across various platforms and healthcare providers, fostering improved collaboration and decision-making processes and elevating patient safety.

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Keywords: Patient-centered care; Network theory; Copula nodes; Cost/Benefit analysis; e-health

1. Introduction

Interoperable multilayer networks are pivotal in transforming public health by enhancing disease control strategies and diagnostic systems (Loza et al., 2012) [1]. By employing computational algorithms to replicate realistic social models of educational institutions, these multilayer networks assist in identifying vulnerable populations and optimizing control measure distribution during disease outbreaks. Moreover, diagnostic systems based on neural networks contribute significantly to detecting health risks such as hypertension, achieving a high level of effectiveness.

These networks enable integrating varied health intelligence data, enhancing disease detection, alerting, response, and prediction capabilities during public health crises. Additionally, implementing data sharing standards and interoperability, coupled with innovative methodological approaches, workforce structures, and data governance, guarantees the security and reliability of public health data systems.

Within this framework, digital health concerns use digital technologies for health. This process involves incorporating different technological tools into healthcare, such as eHealth (Hallberg & Salimi, 2020), mobile health (mHealth), telemedicine (Groom et al., 2021), and utilizing computer science concepts like big data and artificial intelligence (Hyder & Razzak, 2020) [2-4].

This study shows the link between digital health, which is increasingly used in public healthcare, and multilayer networks. These networks consist of advanced structures where multiple layers interact through connecting copula nodes (represented by IT devices, m-Apps, EHRs, etc.).

The multilayer network architecture, characterized by its intricate system of interconnected layers, each serving a specific function, offers a high degree of adaptability, expansiveness, robust security measures, and unwavering dependability essential for accommodating the intricate and demanding specifications inherent in digital health. By enabling efficient data management and communication between various healthcare stakeholders, multilayer networks play a crucial role in expanding access to healthcare services, improving patient outcomes, and making healthcare systems more resilient and cost effective. This multilayer design structure is vital in digital health for diverse services support: Digital health requires transmitting various data types, including voice, video, and significant medical files. Multilayer networks can efficiently handle this diversity by segregating services based on bandwidth and latency requirements and coordinating devices (smartphones, tablets, etc.).

Scalability the ability of an information system to maintain its Equilibrium State with increased storage volume is another core issue that adds flexibility to healthcare ecosystems that can face severe and unforeseen stress (as in the case of pandemics). The demand for digital health services can fluctuate significantly, driven by factors such as pandemics or changes in healthcare policies. Multilayer networks can scale up or down based on demand, ensuring that the network infrastructure can always meet the needs of healthcare providers and patients.

Preserving patient data privacy and security is paramount within the healthcare sector. Multilayer networks can implement advanced security protocols and encryption at various levels offering robust protection against unauthorized access and data breaches. This protection is especially important for sensitive medical data transmitted

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during digital health consultations.

Healthcare services need reliable networks to guarantee uninterrupted digital health consultations and data transfers. Multilayer networks can provide backup solutions, allowing seamless service even if one path or layer experiences issues.

Multilayer networks also prioritize quality of service management, which is crucial for digital health services. This process ensures that high-priority services such as live video consultations always have capacity and speed, even during network congestion.

Consistent with this introductory framework, the paper is structured as follows: digital health and its public health implications will be briefly introduced before a fundamental multilayer network analysis. The two topics will then be jointly examined, analyzing their public implications, even in cost/benefit analysis and scalable digital health ecosystems. A brief discussion anticipates the conclusion.

2. Literature Review

A literature survey on multilayer networks and public digital health scalability should encompass various aspects such as conceptual foundations, technological advancements, practical applications, and their impact on healthcare systems. A proposed structure for the literature survey, along with categorized references, is the following:

2.1. Introduction to Multilayer Networks in Digital Health

- Conceptual Foundations: Barabási (2016); Bianconi, (2018); Barabási & Albert (1999) [5-7].

2.2. Importance and Impact of Digital Health

- General Overviews: Bloom et al. (2023); Channi et al. (2022) [8, 9].

2.3. Interoperability and Data Integration

- Technological Frameworks and Challenges: Lamprinakos et al. (2015); Geng et al. (2024) [10, 11].

2.4. Telehealth and Telemedicine

- Applications and Case Studies: Groom et al. (2021); Dhaduk et al. (2021) [3, 12].

2.5. Patient-Centric Approaches and Outcomes

- Impact on Patient Well-being and Engagement: Poitras et al. (2018); Moro-Visconti (2021) [13, 14].

2.6. Cost Efficiency and Resource Optimization

- Economic Analyses and Reviews: Snoswell et al. (2020); Woods et al. (2023) [15, 16].

2.7. Challenges and Future Directions

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- Barriers and Innovations: Haleem et al. (2021); Rahimi et al. (2023) [17, 18].

By structuring the literature survey according to this canvas, researchers can comprehensively cover the multifaceted aspects of multilayer networks and their transformative impact on public digital health scalability. Each section builds on the previous one, thoroughly understanding these technologies' theoretical underpinnings, practical applications, and future potential in healthcare.

More specifically, this study shows that interoperable multilayer networks play a pivotal role in revolutionizing public digital health by enhancing healthcare service delivery, improving public health outcomes, and contributing to substantial cost savings for public healthcare systems (Channi et al., 2022; Osipov & Skryl, 2021) [9, 19].

These networks facilitate seamless data exchange and integration across healthcare systems and providers, increasing accessibility, efficiency, and data-driven decision-making through advanced technologies like block chains (Geng et al., 2024) [11].

Networks facilitate a more efficient and effective healthcare system by reducing redundancies, optimizing resource allocation, and minimizing unnecessary procedures. They ensure financial sustainability while improving care access and patient engagement, contributing significantly to universal health coverage (Bloom et al., 2023). For example, implementing a national health information system based on interoperable networks in Estonia has improved patient outcomes and reduced administrative costs [8].

Innovative multilayer network analysis is crucial in improving interoperability, reducing spatial and temporal constraints, and streamlining processes within healthcare systems. Blockchains play a key role by providing a secure and transparent method for data exchange, enhancing trust among medical entities, and ensuring data integrity. This technological foundation enables high-quality care delivery at a lower cost and transforms patient care paradigms (van der Weert et al., 2022) [20].

Despite the benefits, implementing interoperable multilayer networks presents challenges. Data privacy concerns, varying interoperability standards, and resistance to change are significant hurdles. Addressing these challenges requires robust data governance frameworks, standardized interoperability protocols, and comprehensive stakeholder engagement strategies. For instance, the Health Level Seven International (HL7) standards have been instrumental in promoting interoperability in healthcare.

Future research should focus on developing more advanced algorithms for network analysis, enhancing data security measures, and fostering international collaboration for global health data interoperability. Emerging trends, such as integrating artificial intelligence and machine learning with multilayer networks, promise to improve healthcare outcomes and efficiency further.

Integrating the multilayer network model into healthcare architectures can comprehensively represent the healthcare system, fostering trust among medical entities and enhancing treatment outcomes (Rahimi et al., 2023) [18]. By addressing current challenges and leveraging technological advancements, interoperable multilayer networks can significantly transform public digital health, ensuring sustainable and high-quality healthcare for all.

This study represents an advance in the current literature, (Moro Visconti, 2021; Pathinarupothi et al., 2016), as it innovatively links digital health studies with multilayer network theory analysis [14, 21].

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3. Digital Health and Public Healthcare

Digital health has transformed public healthcare by significantly enhancing the accessibility of services, particularly benefiting individuals residing in rural or underserved areas with limited medical facilities. Utilizing remote consultations in digital health diminishes the necessity for travel, ensuring prompt care delivery. In times of public health emergencies such as pandemics, digital health services become indispensable for delivering care while minimizing the risks of disease transmission, underscoring their crucial role in emergency scenarios. Additionally, digital health plays a role in addressing healthcare workforce shortages in underserved regions by enabling remote service provision and expanding the reach of specialists beyond conventional boundaries, thereby enhancing the optimization of healthcare delivery. The impact of digital health on public healthcare has been profound and multifaceted, with significant benefits observed in several key areas and some concerns (Jandoo, 2020) [22]. Digital health dramatically enhances access to healthcare services, especially for people living in rural or underserved areas where medical facilities are scarce or hard to reach. By providing remote consultations, digital health reduces the need for travel and helps patients receive timely care. Digital health supports public health by facilitating distance health monitoring, disease management, and health education. During public health crises, for instance, pandemics (Leite et al., 2020), using digital healthcare services becomes imperative to deliver efficient care while reducing the potential for disease spread [23]. By enabling healthcare providers to offer services remotely, digital health can help address the shortage of healthcare professionals in underserved areas, optimizing the workforce. It allows specialists to extend their reach beyond traditional geographic boundaries (Satamraju, Krishna Prasad 2020) [24].

Digital health has the potential to significantly decrease healthcare expenditure by mitigating the necessity for face-to-face consultations, a process known to incur substantial costs and consume a considerable amount of time. Furthermore, it can diminish the financial burden on patients related to transportation expenses, thereby enhancing accessibility to healthcare. The ability for patients to access healthcare services remotely enhances the likelihood of their participation in regular health monitoring and post-treatment care, transitioning from being in-patient or out-patient to home-based patients whenever feasible.

Integrating digital health into the healthcare system optimizes the delivery process, enhancing its effectiveness. It expedites the diagnosis and treatment, diminishes appointment waiting times, and enables more efficient appointment schedule management.

The delivery of healthcare through digital platforms has demonstrated comparable effectiveness to in-person visits, especially within specific medical fields like psychiatry (Smith et al., 2020) and dermatology (Dhaduk et al., 2021) [12, 45]. Furthermore, digital health technologies facilitate consistent healthcare delivery, critical for managing chronic conditions and ensuring patients' overall health.

The adoption of digital health solutions in remote areas has notably enhanced healthcare accessibility by negating the necessity for patients to undertake lengthy journeys for medical appointments. This adoption, in turn, guarantees prompt healthcare provision and alleviates the healthcare burden on individuals in underserved locales.

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This provision highlights the importance of incorporating digital health solutions in emergency response strategies to ensure the continuity of healthcare services. By enabling remote service provision and extending the reach of healthcare specialists beyond traditional boundaries, digital health helps mitigate healthcare workforce shortages in underserved areas. This innovative approach optimizes healthcare delivery and ensures that patients in remote regions can access quality care.

The infusion of digital health technologies into the healthcare sector accelerates diagnosing and treating patients, minimizing waiting times for appointments and refining the management of appointment schedules. This fine-tuning elevates the efficacy of healthcare provision, ensuring that individuals receive prompt and effective care irrespective of their geographical proximity. By streamlining diverse procedures and frameworks, this advancement markedly amplifies the overall efficiency and influence of healthcare delivery, thereby ensuring that patients, regardless of their location, are promptly and effectively catered to with a superior standard of care.

4. Multilayer Networks

The interconnected layers provide insights into relationships, enabling personalized treatment strategies. Real-time data integration enhances decision-making and enables customized care delivery. The interdisciplinary approach ensures comprehensive patient care, especially for complex cases. Machine learning models analyze vast data to provide decision support for proactive patient management. The integration of data sources like genomics and EHRs enables personalized treatment strategies. By incorporating real-time health data, multilayer networks support proactive patient management.

The link between digital health and multilayer networks involves how digital health relies on advanced and interconnected network infrastructures to deliver healthcare services remotely.

Network Science (Barabási, 2016) is a prolific field coming from several disciplines, which is compatible with the increasing use of big data (Bianconi, 2018), even in healthcare (Palanisamy & Thirunavukarasu, 2019) [5, 6, 25]. In the beginning, single networks can be classified as undirected or directed.

Multilayer networks are complex and advanced systems distinguished by many interconnected networks, where each stratum represents a unique classification of interaction, association, or linkage. This system starkly contrasts conventional network models, which typically concentrate on singular connections between nodes; in contrast, multilayer networks encompass multiple strata, with each layer symbolizing a unique form of relationship or interaction between entities. This approach provides a more nuanced and comprehensive understanding of complex systems by examining the intricate interrelations among various layers.

Multilayer networks present a formidable instrument for encapsulating the intricacy of real-world systems, offering perspectives that may not be readily discernible when employing more basic, single-layer network frameworks **(**Orhan,Yunus Emre 2022) [26].

Multilayer networks, also known as multiplex networks according to Bianconi (2018), are intricate mathematical constructs utilized by researchers and professionals to gain insights into, make predictions about, and exert control

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over the complicated dynamics of complex systems spanning a diverse array of fields, such as the realm of public healthcare [6].

The mathematical formulation of multilayer networks involves a meticulous examination of the inter-layer connections between nodes across different layers, contributing to the models overall complexity and richness.

To define copula nodes that connect different layers, we introduce additional nodes, called copula nodes, which serve as bridges between layers. A copula node can be connected to nodes in different layers, facilitating the interaction or information flow between them. The connectivity pattern of copula nodes is typically defined based on the specific application and desired network structure.

One way to represent inter-layer connections in a multilayer network is through inter-layer coupling matrices C, where ′Cll′ denotes the strength of the connection between layer l and layer ′l′. These coupling matrices can model how information or influence propagates across layers. Multilayer networks are dynamic, showing a temporal evolution (incorporating machine learning) and allowing for a combination of synergistic networks linked by connecting copula (replica) nodes.

Multilayer networks' complexity and ability to represent multiple types of interactions, relationships, and connectivity make them particularly suited for digital health applications. They offer a flexible, scalable, resilient framework for integrating diverse data sources and facilitating comprehensive, patient-centered healthcare delivery.

In healthcare and digital health, these layers can represent various data and communication channels, such as EHRs, telehealth video conferencing systems, wearable health devices, and more. Critical characteristics of multilayer networks impacting digital health are reported in **Table 1.**

Table 1. Impact of multilayer networks on digital health.

Feature	Description	Impact on Digital Health
Multiple layers	Each layer in a multilayer network represents a different type of interaction or relationship	Integrating different types of patient data (e.g., EHRs, wearable device data, and social determinants of health) across various layers Interaction modeling across different layers (e.g., information sharing, financial transactions, clinical care), enhancing system analysis and decision-making. Precision medicine, leveraging detailed, multifaceted data Predictive analytics
Nodes	Depending on the network's context, nodes in multilayer	Holistic patient view

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	networks can exist in one or more layers, representing entities such as individuals, organizations, computers, or biological elements	Complex system (cross-layer) insights Integrated care models Targeted interventions System resilience and adaptability Innovation and efficiency Policy and planning Increased complexity in management
Edges	Edges are the connections between nodes. In multilayer networks, edges can exist within (intra-layer edges) or between layers (inter-layer edges), representing within and cross-type interactions	Improved interoperability and data integration Enhanced understanding of healthcare dynamics (comprehensive disease modeling; network analysis for health insights) Personalized medicine and care (tailored healthcare Interventions; predictive models for disease risk, treatment outcomes, and health trends) Operational efficiency and resource allocation Complexity in analysis and interpretation Data privacy and security
Inter-layer connections	These are what distinguish multilayer networks from other network types. They represent the connections between the same entities (or different entities) across different layers, enabling the model to capture the complexity of interactions in systems where entities can be related in multiple ways	Inter-layer connections in multilayer networks profoundly impact public digital healthcare by enabling a more nuanced understanding and management of the complex relationships and interactions within healthcare ecosystems. These connections distinguish multilayer networks from simpler network models by capturing the multifaceted ways entities (e.g., patients, healthcare providers, institutions) interact across different contexts or dimensions. They favor: Comprehensive patient care and health management, with holistic patient profiles and integrated care delivery Enhanced disease modeling and epidemiology with multifaceted disease insights and improved public health surveillance

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		Data-driven decision-making Innovation and research

Some typical applications of multilayer networks in digital health (Balram et al., 2016) include patient interaction networks between patients based on relationships such as social interactions, co-occurrence in healthcare facilities, or shared medical conditions [27].

Other applications refer to understanding the disease spread (through transportation networks, social interactions, and genetic similarities) across different populations or geographical regions. Networks catalyze the integration of heterogeneous data sources such as genomics, EHRs, and lifestyle information to develop personalized treatment strategies and predict patient outcomes, optimizing the allocation of healthcare resources such as hospital beds, medical personnel, and medical supplies by modeling the interconnectedness of healthcare facilities and patient flows.

In the ever-evolving landscape of digital health, unlocking the power of interconnected networks is crucial for optimizing the impact and efficiency of digital healthcare innovations. Interoperable multilayer networks facilitate the integration of disparate healthcare data sources. By enabling seamless data exchange and accessibility across different platforms and systems (e.g., hospital systems, out-patient services, home health care), they support comprehensive patient-centered care (Moro Visconti & Martiniello, 2019) [28]. This integration supports more informed decision-making by healthcare providers and personalized care plans for patients.

The interconnected nature of multilayer networks is a holistic perspective that plays a vital role in facilitating more accurate diagnosis, meticulous treatment planning, and the maintenance of seamless care continuity, all of which are fundamental components of patient-centric healthcare provision (Bestsennyy, Oleg 2021) [29].

Utilizing multilayer networks makes incorporating real-time health data from wearable devices and home monitoring systems into patient records feasible, rendering this information readily available to healthcare providers. Integrating data from wearable devices and other health monitoring instruments with digital health platforms enriches remote patient monitoring capabilities.
Integrating artificial intelligence and machine learning models into multilayer networks can analyze vast amounts of data from various layers to provide decision support, predict health outcomes, and identify at-risk patients (Noorbakhsh-Sabet et al., 2019) [30]. This integration facilitates proactive patient health management and personalized care delivery. Artificial neural networks (Rashida, 2023) emulate the functioning of the human brain by simulating interconnected nodes (neurons) that communicate with each other [31].

Interconnected layered networks foster synergy between diverse healthcare fields by offering a cohesive foundation for exchanging data and facilitating communication. This interdisciplinary approach is essential for comprehensive

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patient care, especially for complex cases requiring multiple specialties.

The multilayered structure of digital health solutions allows for scalability and flexibility, accommodating evolving healthcare needs, technologies, and regulations. This level of flexibility is paramount in ensuring patient-centered care continuity, as Poitras et al. (2018) highlighted in the rapidly evolving digital health domain [13].

Interoperable systems play a pivotal role in diminishing redundancies and inefficiencies within the healthcare sector by facilitating the seamless exchange of patient information among various healthcare entities and environments. Consequently, this integration can reduce healthcare expenditure due to the decreased necessity for repetitive tests and the optimization of care coordination processes.

Patient-centric digital health solutions that leverage interoperable multilayered networks empower individuals to actively participate in managing their healthcare journey. This increased involvement through access to their health records can enhance satisfaction levels and foster greater adherence to prescribed treatment regimens.

5. Multilayer Networks and Public Driven Digital Health

The structured framework of multilayer networks enhances relationships across technological infrastructure, service provision, and accessibility. These networks offer a comprehensive method to grasp complexities in digital health systems, empowering stakeholders to address challenges effectively. These networks encompass patient-generated data, social support, healthcare providers, public health initiatives, and technological frameworks, fostering comprehensive and participatory healthcare frameworks.

The underlying technological frameworks ensure secure data storage, processing, and accessibility for authorized users, enhancing health outcomes and healthcare services.

The complex nature of healthcare systems requires a thorough comprehension of the interconnections in digital health, where multilayer networks play a crucial role in optimizing operations and services. These networks offer a structured framework to improve relationships across levels, from technological infrastructure to service provision, ensuring accessibility, effectiveness, and resilience in challenging circumstances.

The correlation between multilayer networks and digital health traces back to the intricate and interconnected nature of healthcare systems, where digital health functions as a pivotal element essential for the system's operations. Multilayer networks present a structured framework to comprehend and enhance the connections and relationships between various network layers (or types) within a given system. These networks facilitate a deeper insight into the intricate systems supporting digital health and aid in optimizing such systems, ranging from technological infrastructure to delivering services.

Utilizing multilayer networks offers a holistic and all-encompassing method for grasping the complexities inherent in the systems that uphold digital health. These systems encompass everything from the technological backbone to providing services and more. They empower various stakeholders to tackle the multifaceted hurdles present in contemporary healthcare, ensuring that digital health services remain accessible, efficient, and robust in the face of challenges.

This multidimensional discussion sheds light on how these networks impact the digital health landscape and patient-centric care delivery. Public-driven multilayer networks in digital health refer to complex, interconnected systems

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significantly influenced, shaped, or utilized by the general public or patient communities. These networks embody multiple layers of interaction and data exchange, encompassing various stakeholders, technologies, and communication channels in the healthcare ecosystem Evers, (Emily C., et al) [32]. The "public-driven" aspect emphasizes the role of patients, their families, and the broader community in contributing to, accessing, and using these networks, often focusing on enhancing patient care, improving health outcomes, and facilitating public engagement in health-related matters. Interactions include:

- **Patient-Centric Data Layers:** One layer might include patient-generated health data from wearable devices, mobile health apps, or patient-reported outcomes. This layer empowers patients to actively contribute their health data, making them integral participants in their healthcare management.
- **Community and Social Support Layers:** These layers can represent online patient communities, social media platforms, and support groups where patients and caregivers share experiences, advice, and support. Such interactions provide emotional and social support and facilitate the exchange of valuable health-related information and resources.
- **Healthcare Provider Layers:** Traditional healthcare provider networks, including hospitals, clinics, and private practices, form another layer. These institutions may engage with patients via digital health platforms, offering virtual consultations, remote monitoring, and digital health assessments.
- **Public Health and Research Layers:** Public health initiatives and research projects that engage with the public for data collection, health surveillance, and participatory research studies constitute another crucial layer. These efforts can lead to better-informed public health strategies and more targeted healthcare interventions.
- **Technology and Infrastructure Layers:** The backbone of these networks is the underlying technological frameworks that support digital health services, such as cloud computing (Mishra et al., 2019), data analytics platforms, and cybersecurity measures. These frameworks ensure that data is securely stored, processed, and accessible to authorized users [33].

Public-driven multilayer networks in digital health signify a notable transition towards embracing more comprehensive and participatory healthcare frameworks that harness the synergistic potential of technology, data analytics, and community involvement to enhance health results and provide healthcare services. These networks within the domain of digital health present a holistic and all-encompassing approach to managing processes related to homecare assistance, amalgamating cutting-edge technological advancements with data-centric decision-making strategies to efficiently allocate resources, enhance patient care quality, and endorse the de-hospitalization campaign (Massaro et al., 2018) [34].

6. Mathematical Formulation of Multilayer Networks in the Context of Digital Health

The mathematical formulation of multilayer networks in the context of digital health involves several key concepts from network theory, particularly the use of graph theory to represent and analyze the relationships between different layers and nodes within the system. Here is a basic outline of the mathematical framework:

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6.1. Multilayer Network Structure

6.1.1. Nodes and Layers:

- **Nodes:** Represent entities in the digital health system, such as patients, healthcare providers, technological devices, and databases.
- **Layers:** Represent relationships or interactions, such as patient data, social support networks, healthcare provider networks, and technological infrastructure.

6.1.2. Graph Representation:

- A multilayer network can be represented as where the set of nodes ε is the set of edges, and L is the set of layers.
- Each layer can be represented as a graph $G^l = (V^l, E^l)$,

  Where, $V^l \subseteq v \; and \; E^l \subseteq \varepsilon$

6.1.3. Intralyer Edges:

- These are the edges within the same layer *l*.
- Represented as $E^l \subseteq V^l \times V^l$

6.1.4. Interlayer Edges:

- These are the edges between nodes in different layers.
- Represented as $E^{l_1,l_2} \subset V^{l_1} \times V^{l_2} \; for \; l_1, l_2 \in L$

6.2. Adjacency Tensors and Matrices

6.2.1. Adjacency Matrices for Each Layer:

- For each layer *l*, the adjacency matrix A^l represents the interlayer connections.
- $A^l_{ij} = 1$ If there is an edge between nodes *i* and *j* in layer *l*, otherwise $A^l_{ij} = 0$.

6.2.2. Interlayer Adjacency Matrices:

- The interlayer adjacency matrix A^{l_1,l_2} represents the connections between nodes in layer l_1 and layer l_2.
- $B(H) = (e_{1+}e_2 + c_1 + c_2 + i_1) - (s_1 + s_2 + m_1 + m_2 + t_1 + t_2)$ if there is an edge between node *i* in layer l_1 and node *j* in layer l_2, otherwise $A^{l_1,l_2}_{ij} = 0$.

6.2.3. Interlayer Adjacency Matrices:

The entire multilayer network can be represented by a tensor *A*, which A^{l_1,l_2}_{ij} represents the presence of an edge between node *i* in layer l_1 and node *j* in layer l_2.

6.3. Network Dynamics and Metrics

6.3.1. Centrality Measures:

Centrality measures like degree centrality, between centrality, and eigenvector centrality can be

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extended to multilayer networks to identify important nodes across different layers.

6.3.2. Path Analysis:

Shortest path algorithms can be adapted to multilayer networks to find paths that span multiple layers, helping to understand the flow of information or resources.

6.3.3. Community Detection:

Community detection algorithms can identify densely connected node clusters within and across layers.

6.4. Optimization and Resilience

6.4.1. Network Optimization:

Optimization techniques can be applied to improve network efficiency, such as minimizing latency or maximizing data throughput across layers.

6.4.2. Resilience Analysis:

The resilience of the multilayer network can be assessed by simulating failures in nodes or edges and observing the impact on the overall network functionality.

A mathematical formulation example can be the following: Suppose we have a simple multilayer network with two layers: a patient layer P and a healthcare provider layer H.

It is important to start from adjacency matrices concerning:

- Patient layer A^P
- Healthcare provider layer A^H
- Interlayer connections A^{PH} (patients to healthcare providers) and A^{HP} (healthcare providers to patients, often the transposition of A^{PH})

The network representation with an adjacent matrix is:

$$A = \left(\frac{A^P}{A^{HP}} + \frac{A^{PH}}{A^H} \right)$$

The calculation concerns the centrality measures for A^P, A^H, and their combined effects considering A^{PH} and A^{HP}.

This mathematical framework uses multilayer networks to model and analyze the complex interactions in digital health systems. By representing different entities and their interactions across multiple layers, stakeholders can gain deeper insights into the system's dynamics, optimize performance, and enhance resilience.

7. Cost/Benefit Analysis

Integrating electronic health records brings various benefits, such as cost reductions, improved data legibility, and

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enhanced decision-making processes. These benefits highlight the economic, clinical, and informational advantages of digital advancements in healthcare systems.

Multilayer networks amplify healthcare services' effectiveness, availability, and excellence. As demonstrated in **Table 2**, they present a promising avenue for further enhancement in healthcare systems. Incorporating digital health technologies within the healthcare industry has exhibited notable benefits. The utilization of digital health data is pivotal in ensuring cost-effective and efficient healthcare choices, underscoring the significance of unbiased information for all involved parties. Additionally, digital radiography systems provide substantial advantages compared to traditional systems, with reduced expenses and faster amortization periods, signifying their cost-effectiveness and efficacy within healthcare environments.

The inclusion of information technology in healthcare institutions has been demonstrated to enhance service quality, albeit with substantial expenses that necessitate thorough investment validation. Integrating electronic health records produces diverse benefits, including cost reductions, enhanced data legibility, and improved decision-making processes, spotlighting the economic, clinical, and informational benefits of digital advancements in healthcare systems (Hyder, Maryam 2020) [4].

The advantages of using digital health technologies (Woods et al., 2023) are increasingly becoming apparent within the healthcare sector [16]. Multilayer networks play a crucial role in amplifying healthcare provisions' effectiveness, availability, and excellence, presenting a promising avenue for further enhancement in this realm, as shown in **Table 2.**

Table 2. Cost/Benefit analysis of digital health.

Solutions	Description	Benefits	Costs
Integrated healthcare services	Multilayer networks enable the integration of various healthcare services, including primary care consultations, specialist referrals, and emergency services across different platforms and technologies. This integration improves patient care coordination and streamlines healthcare delivery	It enhances patient care continuity, reduces the duplication of services, and improves overall health outcomes	The initial investment in technology infrastructure and ongoing maintenance costs
Data sharing and interoperability	Networks facilitate the sharing of patient data across different healthcare systems and providers, including EHRs, lab results, and imaging studies, ensuring that information is readily available when needed	It improves diagnostic accuracy, reduces unnecessary tests, and speeds up treatment, potentially leading to significant cost savings	Requires investments in secure data-sharing technologies and may involve costs related to ensuring privacy and regulation compliance

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		for healthcare systems	
Remote patient monitoring	Multilayer networks are a sophisticated approach that utilizes interconnected systems to effectively oversee the health status of patients from a distance, using wearable devices and home monitoring equipment. This innovative method is particularly beneficial in managing chronic conditions and providing care to patients after discharge from medical facilities	Reduces hospital readmissions and allows for early intervention, improving patient outcomes and reducing long-term healthcare costs	Initial setup costs for remote monitoring devices and platforms and training costs for healthcare providers and patients are also involved
Public health surveillance	In real-time, Multilayer networks monitor public health data, such as disease outbreaks, vaccination rates, and health trends, to inform public health decisions and interventions	It enables timely and targeted public health responses, preventing or mitigating health crises and saving on emergency response costs	Investment in data collection, analysis tools, and potentially increased surveillance infrastructure is required
Patient Engagement and self-management	Multilayer networks can support platforms that engage patients in their care, including telehealth apps for health tracking, appointment scheduling, and digital communication tools for patient-provider interactions	Preventing complications increases patient satisfaction, improves adherence to treatment plans, and can lead to better health outcomes and cost savings	Development and maintenance of patient engagement platforms and digital literacy programs for some patient populations
Education and training	Supporting continuous education and training for healthcare professionals through online platforms and virtual reality simulations, ensuring they remain current with medical advancements and best practices	Improves the quality of care and patient safety, potentially reducing malpractice and associated costs	Investment in educational content development, technology platforms, and ongoing training programs

While the initial setup and ongoing maintenance of multilayer networks in public digital health require significant investment, the potential benefits of improved healthcare access, efficiency, and patient outcomes can outweigh these costs over time. Additionally, multilayer networks can contribute to long-term savings by reducing unnecessary procedures and hospital readmissions and enabling more effective public health interventions.

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The economic advantages derived from using digital health technologies like e-health, m-health, and telemedicine have been the subject of thorough examination, with numerous crucial statistical data and research projects that illustrate these benefits' significance. Numerous empirical research endeavors have elucidated the transformative impact of digital health technologies on healthcare delivery, shedding light on their propensity to engender substantial cost reductions.

For instance, in their recent study, Evers and colleagues (2022) estimated the potential cost saving implications of telemedicine services as opposed to traditional in-person medical consultations.

Furthermore, a report published by Deloitte in 2015 highlighted the efficacy of remote patient monitoring initiatives in mitigating hospital readmissions by as much as 30% while concurrently generating potential cost reductions amounting to an impressive $10 billion annually, specifically within the healthcare landscape of the United States.

Beyond mere cost savings, incorporating digital health technologies can create novel revenue streams for healthcare providers and other relevant stakeholders.

For instance, McKinsey (2021) estimated that the global telemedicine market could generate $250 billion in revenue annually by 2025 [29]. This forecast underscores the significant economic implications and opportunities the telemedicine industry holds for stakeholders, highlighting the immense potential for financial gains and market expansion within this sector. This growth derives from the rising acceptance and integration of virtual healthcare solutions, such as mobile health applications and wearable gadgets that offer subscription services and in-application purchases.

Digital health technologies have the potential to enhance the operational efficiency present within healthcare systems, thereby leading to significant cost savings and the generation of revenue. For example, Upadhyay (2023) discovered that implementing Electronic Health Records (EHRs) generates cost savings in the US healthcare system, amounting to $81 billion annually [35]. This financial benefit depends on the notable reduction in administrative expenditures and enhanced operational efficiency facilitated by EHR systems. This considerable financial benefit stems from the noteworthy reduction in administrative expenses and the enhancement of operational efficiency through streamlining workflow processes. (Haleem et al., 2021) demonstrated that Telemedicine consultations potentially decrease patient wait times and enhance the volume of patients attended to daily. Consequently, this heightened productivity can lead to a notable increase in the overall revenue generated by healthcare providers [17].

Telehealth services have been associated with improved healthcare outcomes while remaining a cost-effective mode of healthcare delivery (Mahtta et al., 2021) [36].

Digital health technologies improve patient outcomes, which can result in long-term cost savings and revenue generation through better population health management and reduced healthcare utilization. For instance, Kruse et al. (2017) found that telemedicine interventions have been linked with enhanced clinical results and increased patient contentment within various medical fields [37]. Peyroteo et al., 2021 have shown that the application of remote digital health platforms in monitoring chronic conditions can enhance the efficacy of disease management protocols and lower the rate of hospital admissions [38]. Consequently, there is a notable decrease in the overall healthcare expenditures linked to managing chronic illnesses as the emphasis transitions towards preventive healthcare and refined treatment approaches.

Several studies have evaluated digital health investments' Return on Investment (ROI) and found promising returns for healthcare organizations and payers. For instance, Snoswell et al. (2020) estimated that every $1 spent on telehealth could lead to $6 in healthcare cost savings, a significant stride towards a more efficient and effective healthcare system [15].

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Interoperable EHR systems are crucial in reducing redundant medical tests by providing comprehensive access to patient records across healthcare providers. This integrated access significantly minimizes the need for repeated tests, leading to a more efficient and cost-effective healthcare system. According to a report from the Office of the National Coordinator for Health Information Technology (ONC), EHR adoption has reduced redundant medical testing by approximately 10% -15%. (Diaz, Yohanca 2018) [39].

8. Mathematical Reformulation of Cost/Benefit Analysis

Integrating digital health technologies and multilayer networks in healthcare systems can be expressed mathematically through cost/benefit analysis, capturing the economic, clinical, and informational benefits:

8.1. Cost/Benefit Function

Define a cost/benefit function Base Hospital (BH) for a healthcare system H that integrates digital health technologies:

$$B(H) = \sum_{i=1}^{n} b_i - \sum_{j=1}^{m} c_j$$

Where:

b_i represents the benefits derived from the i^{th} digital health technology.
c_j represents the costs associated with the j^{th} implementation aspect (e.g., initial setup, maintenance, training).

8.2. Quantifying Benefits

Benefits can be quantified in various dimensions:

- **Economics Benefits (EB):** Cost reductions form improved efficiencies and faster processing times.

$$EB = \sum_{k=1}^{n_e} e_k$$

where e_k represents specific economic benefits.

- **Clinical Benefits (CB):** Improved patient outcomes and enhanced decision-making.

$$CB = \sum_{l=1}^{n_e} c_l$$

where c_l represents specific clinical benefits.

- **Information Benefits (IB):** Enhanced data legibility and better information access.

$$IB = \sum_{m=1}^{n_i} i_m$$

where i_m represents specific informational benefits.

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The total benefits can then be expressed as:

Total Benefits = EB + CB + IB

8.3. Quantifying Costs

Costs can be quantified similarly:

- **Initial Setup Costs (SC):** Acquiring and installing digital health systems.

$$SC = \sum_{p=1}^{m_s} s_p$$

where S_p represents specific setup costs.

- **Maintenance Costs (MC):** Maintenance costs for system upkeep and updates are ongoing.

$$MC = \sum_{q=1}^{m_m} m_q$$

where m_q represents specific maintenance costs.

- **Training Costs (TC):** Expenses related to training healthcare staff to use new technologies.

$$TC = \sum_{r=1}^{m_t} t_r$$

where t_r represents specific training costs.

The total costs can be expressed as:

$$\text{Total Costs} = SC + MC + TC$$

8.4. Multilayer Network Representation

Incorporate multilayer networks to enhance the analysis:

Let us represent the multilayer network where:

- V is the set of nodes (healthcare providers, patients, devices).
- E is the set of edges (interactions, data exchanges).
- L is the set of layers (interactions such as clinical data exchange, administrative process, and patient communications).

Each layer l contributes differently to the overall benefits and costs' Define Bl and Cl as the benefits and costs associated with layer l.

The total cost/benefit function across the multilayer network can be expressed as:

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$$B(\varsigma)=\sum_{l\in L}\left(\sum_{i=1}^{nl} b_i^{(l)}-\sum_{j=1}^{ml} c_j^{(l)}\right)$$

8.5. Optimization

To maximize the net benefit $B(\varsigma)$, we need to optimize the allocation of resources across different layers and technologies. This can be formulated as an optimization problem:

$$\max B(\varsigma)=\sum_{l\in L}(\sum_{i=1}^{nl} b_i^{(l)}-\sum_{j=1}^{m} c_j^{(l)}$$

Subject to constraints such as budget limits, resource availability, and required service levels.

8.6. Example Calculation

For a specific healthcare system integrating Electronic Health Records (EHR) and digital radiography:

- Economic Benefits: e1 = cost reduction from EHR, e2 = cost reduction form digital radiography
- Clinical Benefits: c1 = improved decision-making from EHR, c2 = faster diagnosis form digital radiography
- Informational Benefits: i1 = enhanced data legibility from HER
- Setup Costs: s1 = initial setup costs EHR, s2 = initial setup costs for digital radiography
- Maintenance Costs: m_1 = ongoing maintenance cost for EHR, m_2 = ongoing maintenance cost for digital radiography
- Training Costs: t_1 = training cost for EHR, t_2 = training cost for digital radiography

Thus:

$$B(H)=(e_1+e_2+c_1+c_2+i_1)-(s_1+s_2+m_1+m_2+t_1+t_2)$$

The mathematical framework for cost/benefit analysis in integrating digital health technologies within multilayer networks allows for a comprehensive evaluation of the economic, clinical, and informational benefits against the associated costs. Healthcare systems can significantly improve effectiveness, availability, and excellence by optimizing resource allocation and understanding the interdependencies between different layers.

9. Scalable Digital Health Ecosystems

Integrating multilayer networks fosters collaborative interactions among stakeholders, leading to innovative healthcare solutions. Overcoming data diversity and multidimensionality obstacles is crucial for efficiently managing healthcare big data. Effective sharing of inter-organizational digital transformation knowledge is essential for successful implementation and expansion within scalable digital health ecosystems. These challenges underscore

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the need for knowledge-driven frameworks and collaborative interactions to propel progress in healthcare delivery and responsiveness to unforeseen crises.

Scalable digital health ecosystems entail amalgamating multilayer networks to augment healthcare innovation and resilience. These ecosystems utilize digital platforms to facilitate interactions among diverse stakeholders, establish a web of value exchange, and create inventive healthcare solutions.

Multilayer networks are connected through copula nodes, which improve the overall scalability of the whole ecosystem (with additional nodes and links connecting adjacent layers). **Figures 1 and 2** explain the value creation process when introducing digital health platforms, linking previously unrelated layers, and modifying the healthcare ecosystem accordingly.

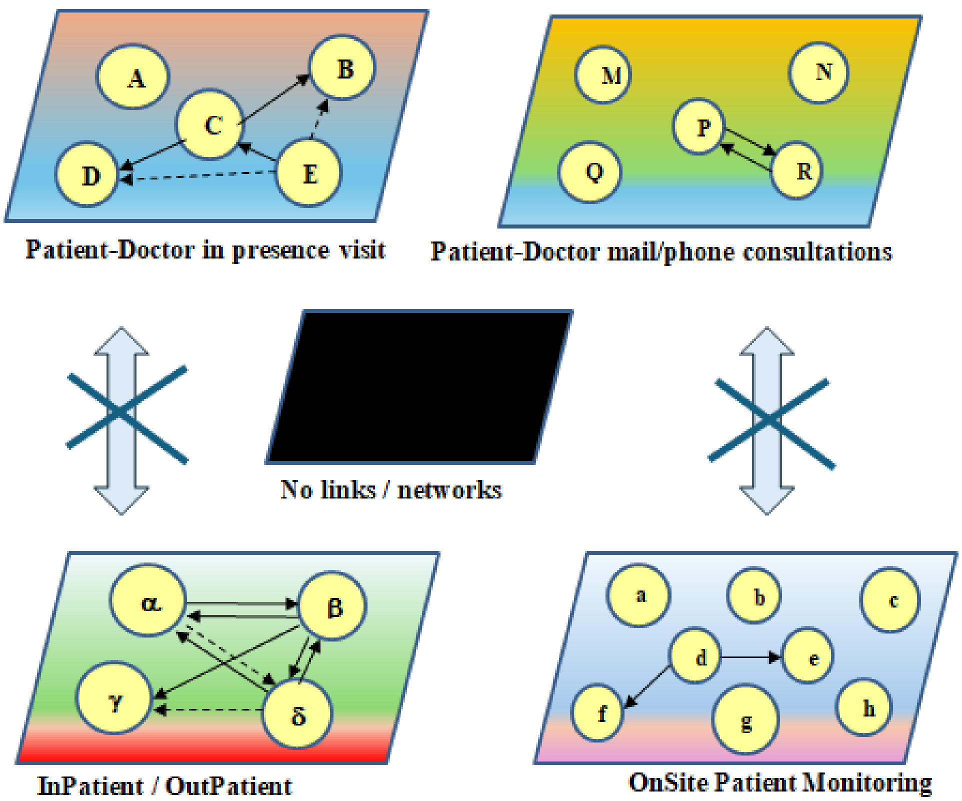

Figure 1. Patient-doctor interactions without digital health.

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The obstacles encountered within these ecosystems encompass data diversity, multidimensionality, and the need for knowledge-driven frameworks to handle unstructured healthcare big data proficiently. Moreover, mechanisms that underpin the sharing of inter-organizational digital transformation knowledge within these ecosystems are indispensable for effective implementation and expansion, underscoring the significance of formal and informal networking in expediting learning and knowledge dissemination. Through the integration of multilayer networks and the cultivation of collaborative interactions, scalable digital health ecosystems have the potential to propel progress in healthcare delivery and responsiveness to unforeseen crises.

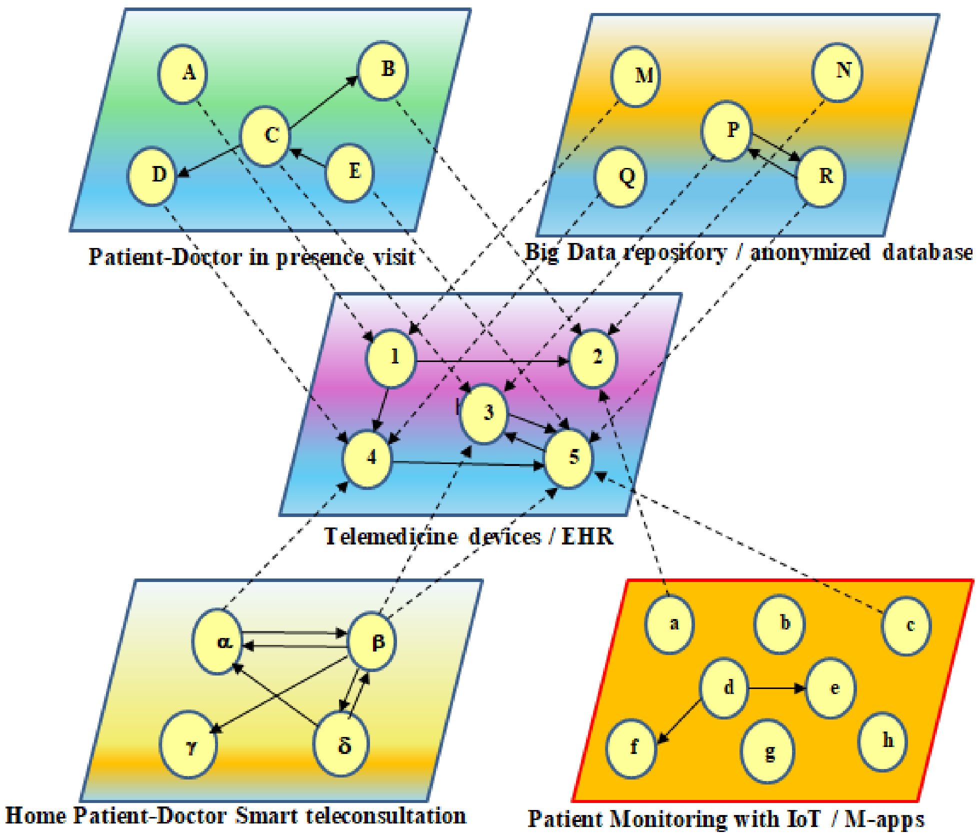

Figure 2. Patient-doctor interactions with digital health devices.

Building up the adjacent (block) matrices corresponding to the above networks shows the increase in edges in the economic system.

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A "with-or-without" differential (incremental) approach, consistent with the International Valuation Standard 210 applicable to intangibles, can be used. Compare **Figure 1** (where layers are not connected) with **Figure 2** (where digital health applications leverage scalable interactions among adjacent layers through connecting copula nodes).
Synergies, in the form of economies of scale and experience (horizontal and vertical scalability), value co-creation patterns (where patients interact with doctors and devices, providing information and receiving feedback), and real options (to expand or suspend the investments, according to their outcome) positively influence the public healthcare ecosystem, in terms of cost savings, improved performance, and value for money.

10. Discussion

Using computational algorithms in multilayer networks plays a crucial role in identifying vulnerable populations. Neural networks, for instance, significantly contribute to the high effectiveness of detecting health risks like hypertension, thereby improving patient outcomes. Integrating varied health intelligence data further enhances disease detection and prediction capabilities, underscoring the potential of digital health to improve healthcare services and patient outcomes (Fareed, Mohammad, & Ali A. Yassin) [40].
The application of network theory in digital health provides notable benefits; however, implementing interoperable multilayer networks encounters obstacles that require thorough examination. Investments in standardized data formats and protocols are essential to improve data processing capabilities, ensure accessibility, and enhance overall data quality within healthcare institutions. Regulatory frameworks supporting data interoperability while preserving patient confidentiality are critical for advancing patient-focused digital health solutions. Fog computing provides a potential solution by bringing computing services closer to end devices in healthcare settings, addressing challenges such as data security, interoperability, and infrastructure support for IoT devices.
While the potential advantages of utilizing network theory within digital health are undoubtedly substantial and promising, the journey toward executing interoperable multilayer networks is challenging. These obstacles necessitate careful consideration and a determined commitment to overcome them, ensuring the successful implementation of digital health solutions.
These challenges notably involve intricate data privacy and security matters, which are paramount in safeguarding sensitive information. They also include establishing standardized data formats and protocols to ensure seamless interoperability and exchange among various systems and platforms. Such investments are essential for enhancing data processing capabilities, providing data accessibility, and promoting overall data quality within organizations. Additionally, regulatory frameworks that support data interoperability without compromising patient confidentiality are needed.
Interconnected networks across multiple layers are vital in shaping innovative digital healthcare solutions to prioritize patient needs. They enhance the quality and efficiency of healthcare delivery, improve patient outcomes, and enable more personalized and accessible care. As technology evolves, the importance of interoperability in healthcare will continue to grow, highlighting the need for ongoing efforts to improve data sharing and system integration.
Multilayered networks elevate the fusion of data, empowering bespoke and seamless healthcare while facilitating timely actions. However, embracing these advantages demands tackling technical, regulatory, and operational hurdles.

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Digital health devices can conveniently use fog computing (Mutlag et al., 2019) an architectural framework that brings computing, storage, and networking services closer to the end devices or "the edge" of the network [41]. It acts as an intermediary layer between cloud data centers and IoT devices. In healthcare, fog computing can process data locally on smart devices or nearby computing nodes, reducing the reliance on distant cloud servers. This proximity to data sources allows quicker response times, crucial in medical emergencies. While fog computing and IoT offer significant benefits for smart healthcare, there are challenges to address, including interoperability between devices, data security concerns, and robust infrastructure to support these technologies. Moreover, ensuring the reliability and accuracy of IoT devices is critical for making life-saving decisions in healthcare.

11. Conclusion

Interoperable multilayer networks significantly impact public health outcomes by enhancing the coordination and efficiency of health services, although their effectiveness can vary based on implementation and usage. These networks, characterized by directed links within and across layers, are crucial for understanding complex epidemiological scenarios, such as the spread of multiple disease strains or interactions between pathogens. These networks facilitate real-time decision-making and resource allocation by integrating data from various sources, which is essential for managing public health crises. For instance, computational tools that model social interactions in schools can identify at-risk populations and optimize intervention strategies, thereby mitigating the spread of infectious diseases among highly susceptible groups like children. Moreover, community-based initiatives supported by interoperable networks aim to address social, economic, and environmental risk factors, promoting health equity and improving overall community health outcomes. However, the effectiveness of these networks in improving patient safety and service coordination remains under-researched, with evidence suggesting that professionals often find them challenging to use, which can limit their potential benefits. Therefore, while interoperable multilayer networks promise to enhance public health outcomes through better data integration and coordination, further research is needed to optimize their implementation and fully realize their benefits.

The correlation between digital health and multilayer networks lies in the significant potential of interoperable networks to completely revolutionize public health outcomes and the delivery of healthcare services. Multilayer networks are instrumental in bolstering accessibility, streamlining processes, and promoting data-informed decision-making within public digital health.

These networks facilitate smooth data exchange and seamless integration across various healthcare systems and providers, resulting in considerable cost reductions, eliminating redundancies, optimizing resource distribution, and reducing unnecessary procedures. Through the implementation of cutting-edge multilayer network analysis techniques, public digital health initiatives can secure financial viability, enhance interoperability, and boost operational efficiency, thereby bringing about a fundamental shift in the delivery of patient care and promoting a patient-centered approach.

The seamless integration of telehealth and telecare in digital health transcends boundaries, enabling continuous patient-doctor interactions. Utilizing anonymized healthcare big data, validated by blockchains and analyzed with artificial intelligence, enhances scalability and efficiency in healthcare systems.

Multilayer networks act as a crucial bridge, simplifying the incorporation of digital health technologies and enhancing the delivery of remote healthcare services. Prioritizing network stability, security, and proactive maintenance enhances the reliability and effectiveness of digital health services.

Digital health integrates telehealth and telecare into a unified platform, transforming patient-doctor interactions by

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surpassing spatial and temporal limitations, expanding connections, and enriching relationships. Utilizing anonymized healthcare big data, verified through block chains and interpreted using artificial intelligence, produces scalable advantages for the healthcare system.

This strategy facilitates remote health monitoring, providing accessibility, cost-efficiency, continuous surveillance, early identification, data-informed decision-making, patient empowerment, and expandability. Multilayer networks serve as a link, easing the integration of digital health technologies and improving the provision of remote healthcare services.

This novel approach emphasizes network stability, security, usability, and proactive upkeep, enhancing digital health services' dependability, efficiency, and efficacy and ultimately elevating healthcare provision and patient outcomes.

Digital health is a powerful catalyzer of patient-doctor interaction, bypassing spatial and temporal limits (anywhere, anytime, 24/7) and increasing the number of nodes (patients, doctors, other stakeholders, devices, etc.) and their edging relationships. Anonymized healthcare big data collected in repository databases can be validated with block chains and interpreted with artificial intelligence algorithms. This validation produces valuable and scalable effects that benefit the whole healthcare ecosystem.

Remote health monitoring offers numerous benefits, including accessibility, cost-effectiveness, continuous monitoring, early detection, data-driven decision-making, patient empowerment, and scalability (Pramanik et al., 2019) [42].

Integrating telehealth and telecare into a cohesive platform for the healthcare monitoring sector represents a significant advancement in personalized and preventive care, particularly for older people. When effectively combined, these technologies can offer a comprehensive view of an individual's well-being, encompassing physical, mental, and psychological health (Lamprinakos et al., 2015) [10].

Digital health implementation requires significant adjustments in technology infrastructure and organizational processes (Alami et al., 2019) [43]. Through their connecting interlayer copula nodes, multilayer networks represent a bridge that eases adoption, softening technical and operational bottlenecks.

The link between digital health and multilayer networks fosters the successful delivery of remote healthcare services. Multilayer networks provide the necessary infrastructure to support the diverse, scalable, secure, and reliable operation of digital health, enabling healthcare providers to offer superior care to patients remotely.

New research avenues may well investigate the advances made possible by artificial intelligence interpretation, block chain validation, and interoperable data warehousing in the cloud, and other digital asset processes. In terms of improved quality, timeliness, and cost savings, the public utility follows as a natural byproduct of these value co-creating patterns, where complementary stakeholders interact, rotating around a patient-centric approach.

The digital health system driven by multi network integration and remote control offers a comprehensive solution to common challenges encountered in traditional digital health setups (Wang et al., 2023) [44]. By prioritizing network stability, interconnection, remote management, security, usability, and proactive maintenance, this innovative approach enhances the reliability, efficiency, and effectiveness of digital health services, ultimately improving healthcare delivery and patient outcomes.

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