Cloud Adoption in Low Resource Settings: A Case Study of Higher Education Institutions in Uganda

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Abstract. Cloud computing has experienced substantial growth in the past decade, and it is projected that the global public consumption of cloud services shall persistently soar to annual unprecedented levels. This growth has prompted significant investments by cloud providers in infrastructure and service portfolios, highlighting the increasing relevance, reliance and adoption of cloud solutions. However, research on cloud adoption reveals notable disparities between developed and developing economies, emphasizing the importance of understanding contextual trends, barriers and opportunities. In this study, we focus on higher education institutions in Uganda and conduct surveys from readiness, implementation and usage dimensions. Our findings indicate that 88% of the institutions are in the early stages of cloud adoption, representing infancy in this context. Additionally, the results provide key inputs in our novel attempt to define a cloud adoption assessment tool for higher education institutions in low resource settings. Finally, and based on our research, we offer recommendations to improve assessment scores and foster increased cloud adoption within these settings.

Keywords: cloud · adoption · higher education · developing economies · low resource settings · assessment

1 Introduction

Cloud computing revolutionizes the way Information and Communications Technology (ICT) resources are accessed and utilized, offering flexible on-demand access to a comprehensive size and range of infrastructure, software, platforms, storage, and applications through network-based provisioning [1] [2]. From

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Infrastructure as a Service (IaaS) to Anything as a Service (XaaS), the evolution of cloud computing has brought about a paradigm shift, transforming daily online operations [3]. This transformation has empowered organizations and individuals to leverage a diverse range of cloud services, enhancing productivity, efficiency and innovation [5]. The cloud has become an integral part of modern technology ecosystems, driving digital transformation and reshaping how we work, collaborate and interact online [4]. With application domains spanning big data computing, health, private sector, government, artificial intelligence and education [8], the global cloud market is projected to grow at an annual rate of over 21.3% by 2024 [6]. Public and private cloud providers have made substantial investments to enhance their service offerings, driven in particular by potential gains en masse. As of 2023, Amazon Web Services (AWS) plans to launch five new global data centers [10], signifying ongoing investment in its cloud infrastructure footprint. Other major public cloud providers like Microsoft Azure and Google Cloud are adopting similar strategies with billion-dollar investments in data center infrastructure. These efforts reflect their anticipation of increased demand and adoption of cloud services. This signifies the relevance of cloud adoption studies for all business domains, regardless of the operational environment.

Public cloud infrastructure in low resource settings is limited due to strategic positioning of cloud providers in demand-intensive locations. Cloud regions, which are geographical locations where cloud providers operate physical data center infrastructure, play a crucial role in determining the quality and availability of cloud services. Out of the 127 operational regions across major cloud providers like AWS, Microsoft and Google, only three regions are located in Africa, representing only 2.4% of the total [33]. Additionally, there are currently no available cloud regions in other African countries, outside South Africa. The connectivity and data center power challenges of these settings haven't helped the cause, further affecting adoption of cloud services. One of the most recent approaches in software development and deployment that leverages cloud computing principles and technologies to build and run applications is cloud-native. It involves designing applications specifically for deployment in cloud environments, taking advantage of the scalability, flexibility, and resilience offered by cloud platforms [13,15]. Ideally, cloud-native application development and deployment principles are a best fit for low resource settings. This is because applications can easily move, for example, between unreliable resource pools. In addition, the lightweight nature of the applications provides for optimized resource utilization in a rather erratic, constrained and unpredictable environment. Gaining an understanding of the current state of cloud computing and cloud-native technologies in low resource contexts is paramount to its adoption.

Cloud Adoption in Higher Education Institutions

In the field of education, the cloud has found extensive use in collaboration, storage, learning management systems, gaming, mobile computing, data analytics, online libraries and digital content management [9]. The ubiquitous operation mode of the cloud can support collaboration between and within the institutions. This involves the use of tools such as online cloud drives (Google Drive, OneDrive), video/web conferencing (Zoom, Microsoft Teams) and source code version control systems (GitLab). Cloud infrastructure and applications can also be shared amongst researchers from different institutions collaborating on similar artefacts. Higher Education Institutions (HEIs) can play an important role in driving the advancement, utilization, and adoption of emerging technologies. Grid Computing, a cloud computing predecessor, originated as a research project at the University of California, Berkeley. The evolution of the Internet, now serving as a medium for provisioning and accessing cloud resources, owes much to collaborative research efforts between the Advanced Research Projects Agency Network (ARPANET) and various universities in the United States. In usage, HEIs have requirements for computation-intensive research operations in fields such as Artificial Intelligence (AI), Simulation, and Modeling, and the cloud is the native computing platform. Moreover, the adoption and usage of cloud services in the education sector can have a ripple effect on the wider industry. While the specific needs for cloud utilization may vary, the significance of the cloud transcends the wider economic and geographical divide.

Within the context of developing economies, new research areas emerge. These include cloud adoption trends, edge computing, low resource cloud networks, relationship between adoption and resources, barriers to adoption, cloud service opportunities and use cases. The abundance of research on cloud adoption in various domains (such as SMEs, commercial banks, health, and education) and regions (for example country-specific studies) [8,28–32] underscores the need for a contextual approach to comprehend the specific factors influencing cloud adoption. In addition, HEIs require comprehensive cloud adoption assessments to guide their future endeavors in the cloud. These assessments can provide valuable direction and insights for institutions as they navigate their cloud adoption journey. Examining practical use cases of cloud technology can offer insights into the state of cloud adoption within HEIs. Our focus in this study is universities in Uganda, and delves into the cloud adoption landscape in this and similar contexts.

Research Questions

This study seeks to answer the following research questions (RQs):

1. *RQ1: What strategies have been employed by higher education institutions in Uganda to facilitate the adoption of cloud technologies?*
2. *RQ2: How are higher education institutions in Uganda utilizing cloud and cloud-native technologies?*
3. *RQ3: What is the current state of research and teaching in cloud-based technologies in higher education institutions in Uganda?*
4. *RQ4: What are the main challenges and opportunities associated with the adoption of cloud technologies in higher education institutions in Uganda?*

We conducted two surveys, over a span of two years, to assess the state of cloud computing and cloud-native adoption in higher education institutions in Uganda. Our research findings provide insights into the current landscape of cloud technology and its future prospects within the context of a developing nation. We identify the challenges and opportunities that exist for enhancing cloud adoption and utilization in this setting. While there have been efforts to establish a standardized maturity model for cloud adoption [19,35], we recognize that its applicability can be subjective and varies across different application domains. This observation aligns with the diverse range of research publications addressing cloud adoption [21–25]. Based on the survey results, we develop a novel cloud adoption assessment tool specifically tailored for HEIs in low resource settings.

Organization of the Paper

The rest of the paper is organized as follows: Sect. 2 provides the related work, Sect. 3 describes the methodology, Sect. 4 details the findings of the study, Sect. 5 describes the cloud adoption assessment tool, Sect. 6 presents our future outlook, and Sect. 7 is the paper conclusion.

2 Related Work

The importance of cloud computing in driving sectoral transformation at the national and regional levels cannot be overstated. Countries and organizations worldwide have recognized the value of cloud technology, transitioning to elaborate cloud usage, as a testament to its significance [6]. Extensive research and industry efforts have been dedicated to exploring cloud adoption in various domains and contexts. These endeavors have yielded frameworks [34], models, strategies, and insights into the challenges, trends, and contextual factors associated with cloud adoption. It is worth noting that disparities in cloud adoption exist between developed and developing economies, with low-income countries often facing greater challenges in adopting cloud technologies [26,27]. Investing in research and higher education has emerged as a promising approach to accelerate cloud adoption [26]. Additionally, public cloud providers have developed adoption frameworks to assist organizations in migration and utilization of cloud services [19].

In the adoption journey of developing economies, unique challenges such as high anticipated costs and network connectivity limitations pose obstacles that hinder the full benefits of cloud services for many users. However, over the past decade, cloud adoption has gained significant research attention. In the case of Ghana and Kenya, organizational challenges and institutional forces (coercive, normative and mimetic) have played a key role in shaping the cloud adoption landscape [28,29]. Despite arguments of stagnation, there have been notable strides in cloud adoption [8], albeit at a relatively slow pace. To gain a better understanding of cloud adoption, it is essential to consider contextual and sector-specific use cases. In this regard, the education sector holds particular significance as it serves as a primary provider and pipeline for technical resources, research artefacts, expertise and a consumer of cloud compute and storage services.

Researchers have investigated the adoption of cloud computing in higher education institutions located in low income countries. In the Philippines, slow internet connections and limited awareness of cloud computing have been identified as factors negatively impacting adoption [30]. Similarly, in Malawi, technological challenges (such as operational skills), organizational factors (including management support), and environmental factors (such as high bandwidth costs) have influenced cloud adoption [31]. Similar studies have been conducted in Kenya, where researchers examined the barriers to cloud computing adoption in higher learning institutions and proposed recommendations. The identified barriers include concerns related to data security and confidentiality [32]. Our work in adoption goes further to assess the state and readiness of institutions for cloud-native technologies. Additionally, we advance a novel cloud adoption assessment tool for institutions in these settings.

In Uganda, cloud adoption has attracted research attention across various sectors, including SMEs, commercial banks, health, and education. Researchers, such as Onayemi *et al.*, have employed the Diffusion of Innovations Theory (DIT) to assess the gradual change and identify challenges in cloud adoption for SMEs, highlighting future uncertainties as a major barrier [21]. Kasse *et al.* emphasize the overall recognition of cloud computing by SMEs and propose a validated framework to enhance its adoption [25]. Mpanga *et al.* focused on lower government agencies in Uganda, using an Enterprise Resource Planning (ERP) system as a motivating use case to explore the contextual adoption of cloud-based systems [22]. Mugyeni discussed the potential benefits of cloud computing for commercial banks and suggested adoption strategies along with a system deployment scenario [23]. The adoption of cloud-based eLearning platforms in higher education institutions is also examined in a study by Etengu *et al.*, where the authors proposed a framework to deliver education activities and resources through the cloud [24]. While Service Oriented Architectures (SOA) are often compared to cloud-native approaches, it is important to assess institutional capabilities and requirements to drive this forward. Moreover, our focus is on exploring adoption within the intersection of perception, practical usage and trends in higher education institutions.

3 Methodology

3.1 Data Collection

In Uganda, there are 53 universities accredited by the Uganda National Council for Higher Education (UNCHE) [16] - a government entity tasked with regulation of higher education institutions and constituent programmes. Of the total, 9 are public (government-funded) and 44 are private institutions. These institutions run various degree and diploma programmes to approximately 200,000 registered students in Uganda. The institutions are located in all the 4 regions of the country (East, West, Central and North) with the central accounting for over 50%. Government institutions are entitled to the National Backbone Infrastructure (NBI) [17] - an optical fiber network that connects all major towns in the country. The NBI project is expected to cumulatively cover 3,156 km across the country with the current completion at 82%. The research and Education Network for Uganda (RENU)[1] connects over 66% of the universities (public and private) to a single national network providing upstream connectivity and other collaboration services to support research and education.

In this study, we conducted two surveys to investigate cloud adoption from both visionary and applied perspectives. The first survey, conducted in 2021, aimed to assess the preparedness and current state of institutions regarding cloud migration across various domains using the AWS Cloud Adoption Framework [19]: Applications and infrastructure, business (need for cloud migration), people (cloud-related roles), process (workflows), operations (governance), and security (secure cloud transactions) [18]. The strategic alignment of these domains is crucial for enabling organizations to derive maximum benefits from cloud services. The survey would further provide a baseline understanding of cloud to an institution, implications on business processes and adoption challenges. In the second survey, we set cloud-native application development and deployment and associated DevOps practices as the median bar to evaluate the current state of cloud and institutional readiness to adapt to its dynamism. The level of research and teaching in cloud and associated technologies is further explored. The latter parts of the survey determine the cloud-native adoption challenges and opportunities for institutions to leverage.

To conduct the two surveys, we developed and validated an online questionnaire that was distributed via email to participants representing ICT operation teams in all the 53 higher education institutions in the country. The survey comprised a combination of quantitative and qualitative questions to gather detailed insights and provide for open-ended views. The participants primarily consisted of ICT technical personnel working in systems and network support departments. Since the teams within each institution are relatively small, targeted sampling was preferred as the most suitable approach. The administrative divide between institutional management and the operations support teams is minimal, enabling a strong likelihood of capturing management viewpoints directly from the support staff. In order to gather comprehensive data and improve response rates, face-to-face interviews were conducted alongside the questionnaires. These interviews served as a means to seek further guidance and gather additional perspectives as deemed necessary by the research team.

3.2 Data Analysis

A total of 26 institutions provided responses to the survey and subsequent analysis was done. To ensure privacy, unique identifiers were assigned to the

[1] https://renu.ac.ug/.

institutions, as stated in the questionnaire preamble. The responses were categorized and recorded using a simple naming scheme: [Category][Question Number][Response]. The respondents included ICT departmental heads/managers, network and systems administrators, systems analysts, IT and planning officers, eLearning coordinators and technicians. Due to the manageable number of responses, a manual walk-through procedure was employed for each institution and responses mapped to a Google Sheets template. Additionally, textual analysis was conducted on the open-ended questions to identify relevant keywords related to the research domain. The closed questions such as those requiring option selection were numerically coded, for example, Yes - 1, No - 0 and Maybe (or not sure) - 3. In Sect. 4, we provide a detailed report of the findings.

3.3 Limitations

The response rate, accounting for 49.1% of the total institutions, may not present a complete view of the current state. However, it is important to highlight that the representation of public institutions in the responses is 100%. The respondents from institutions encompass a diverse range of roles, including managerial and support staff, which may introduce bias in certain question responses. It is worth noting that in smaller institutions, similar personnel often perform multiple roles. The timing of the first survey coincided with the end of the COVID-19 pandemic, which may have affected the response rate and influenced the responses themselves due to the lingering impact of the pandemic. The research team conducted physical interviews across the country, where possible, for additional information.

4 The State of Cloud Adoption in Low Resource Settings

The state of cloud adoption in low resource settings can be established from different perspectives including the adoption strategies, its relevance and use cases in an educational environment, management of supporting infrastructure and integration of evolving cloud technologies. We present our survey findings in the next subsections, aligned with research questions in Sect. 1:

4.1 RQ1: Cloud Adoption Strategies

Overall, cloud adoption in higher education institutions in Uganda is still in its early stages. There is a variation in the understanding of cloud computing and its significance among different institutions. However, each institution tends to utilize some form of cloud service to enhance its business processes. While there are instances of cloud use within these institutions, the absence of formal adoption structures, such as business cases (39% of the institutions), indicates lack of comprehensive plans and strategies for cloud adoption. For example, in our first survey, one of the institutions had expressed no intention to adopt cloud services. However, in the follow-up survey, progress was observed as the institution was using IaaS and SaaS cloud services. It is noteworthy that most institutions (61%) that identified business needs for cloud adoption subsequently developed business cases to support their transition to the cloud. This signifies a positive shift towards recognizing the benefits and relevance of cloud technologies in enhancing institutional operations. On the downside, less than 40% of the institutions had assigned personnel to lead the cause for cloud adoption with a meagre 26% having formulated any change management plans.

Data security and privacy are major barriers to cloud adoption, as highlighted by the survey results. While a majority of the institutions (57%) have an understanding of secure cloud operations, the number of institutions with personnel certified in cloud security is quite low at 4%. Moreover, a majority of institutions (over 85%) lack documented plans or methodologies for cloud security. In addition, the role of institutional management is important in driving adoption strategies, development and implementation of security policies. The survey results, however, reveal that a higher number of institutions (74%) have not obtained leadership approvals for creating security policies or guidelines, suggesting a potential lack of managerial support. The persisting challenges in security, coupled with the disconnect between management and security practices, may hinder the progress of cloud adoption. It is essential for all stakeholders to actively engage in the adoption process, enabling informed decision-making and shaping the future direction of cloud adoption.

HEIs have taken various approaches to cloud adoption, ranging from use of local infrastructure to cloud-native solutions. From the results, one institution is exclusively using public cloud services for its business processes. However, for most institutions, the initial step involves virtualizing existing local infrastructure using open source tools like Proxmox[2]. By virtualizing their infrastructure, these institutions can optimize resource utilization, although it may come at the expense of potential failure points. To ensure improved availability, resources can be clustered to provide redundancy. The next phase may involve establishing a local private cloud, which requires expertise in setting up and administering the different components that form a "cloud" environment. Achieving high availability necessitates additional investment in resources located in diverse locations, as well as a robust supporting network. As an example, one institution has implemented an OpenStack[3] cloud that spans two sites. 61.1% of the institutions use collocation services with 75% in-country, 8.3% out-country and 16.7% either option. The government of Uganda through the Ministry of ICT & National Guidance and its agency, the National Information Technology Authority (NITA-U)[4], RENU and Raxio Uganda[5] are the prevalent collocation service providers that institutions use. NITA-U serves government Ministries, Departments and Agencies (MDAs) including public higher education institutions. The final stage of cloud adoption involves leveraging either a public or private cloud

[2] https://www.proxmox.com/en/.
[3] https://www.openstack.org/.
[4] https://www.nita.go.ug/.
[5] https://www.raxiogroup.com/.

service provider to host certain institutional services. This transition may eventually involve incorporating cloud-native principles for orchestrating and managing services deployed in the cloud. The process typically follows a pipelined approach with controlled operations to ensure smooth integration and operation within the cloud environment.

4.2 RQ2: The State of Cloud and Cloud-Native

Cloud Relevance and Cost 'Myths': HEIs in Uganda are using cloud services for a range of applications and operations. From eLearning systems to disaster recovery management, the cloud is gaining traction. Other key use cases include storage, real-time communication, collaboration tools, and institutional management systems. One of the notable advantages of cloud adoption is high system availability, which enhances resilience. In contrast, locally hosted deployments often face challenges such as limited resources, equipment theft, power fluctuations, and restricted bandwidth, leading to service access issues. These are typical challenges of a low resource environment. The survey results indicate that cloud adoption brings about cost reductions in infrastructure management, including the purchase, maintenance, and management of equipment. However, there are differing views on the overall costs associated with cloud adoption and maintenance. While many believe that the cloud offers cost advantages, especially in terms of managing infrastructure, users remain skeptical with concerns about potential long-term costs and the fear of being locked into services that could become expensive in the long run. In settings with highly restrictive ICT budgets, the cost dimension becomes a significant hindering factor to cloud adoption.

Despite cost and access barriers, HEIs consider cloud adoption as integral to supporting institutional operations. The cloud's high system availability ensures continuous access to critical services such as learning management systems and communication platforms, minimizing downtime and disruptions. Scalability and elasticity are additional advantages, allowing institutions to easily adjust their computing resources based on changing demand. During peak periods, such as enrollment or exam seasons, institutions can scale up resources to accommodate increased workloads. Conversely, they can scale down during periods of lower demand to optimize resource utilization and cost efficiency. Cloud-based disaster recovery solutions offer reliable data backup and recovery mechanisms, enabling institutions to protect against data loss caused by hardware failures, natural disasters, or other unforeseen events. Moreover, cloud-based collaboration tools and real-time communication platforms foster seamless teamwork and knowledge sharing among students, faculty, and staff, irrespective of their physical locations. These tools enhance learning and administrative processes by facilitating effective collaboration and communication.

Cloud-Native: Cloud-native refers to an advanced utilization of cloud technology that leverages containerization for streamlined application development and deployment. In this approach, developers encapsulate applications into microservice abstractions, which are executed as containers, enabling portability across different platforms with similar run-time environments. By incorporating principles and practices of Development (Dev) and Operations (Ops), cloud-native solutions significantly enhance product-to-market timelines, reducing them by up to 30% and yielding additional cost savings in production [20]. Moreover, containerization enables more efficient resource optimization, particularly important in resource-constrained environments. However, it is important to acknowledge the collaborative effort required among development teams to implement new application features. The cloud-native approach necessitates a focus on local development efforts and a dedicated team responsible for the application's life-cycle. Conversely, proprietary software may not offer the required customization flexibility to align with this paradigm.

Among the respondent institutions, 55.6% have locally developed software systems, while the remaining half primarily rely on proprietary software. This poses challenges in implementing and managing cloud-native development and deployment concepts. For institutions with local development, software releases are predominantly manual and vary in frequency, ranging from a few weeks to quarters, with minimal updates to application functionality. Only 16.7% of the institutions employ some form of Continuous Integration/Continuous Deployment (CI/CD) tools in their software release cycles, with Docker, Github, and Jenkins being the most commonly used. Regarding application containerization, most institutions have future plans to integrate it into their Proof of Concept (PoC), development, testing, and production environments, as depicted in Fig. 1 and Table 1. However, over 72% of the institutions currently do not utilize application containerization for the majority of their application requirements. The reasons for this limited adoption or deployment include lack of capacity and skills, complexities in networking and service discovery, storage management issues, and challenges related to vendor and legacy system support.

Table 1. The state of Cloud-Native in HEI in Uganda

Stage	Current Use (%)	Future Plan (%)	No Plan (%)
Proof of Concept	11.1	61.1	27.8
Development	16.7	44.4	38.9
Testing	16.7	44.4	38.9
Production	16.7	50.0	33.3

4.3 RQ3: Applications, Learning and Research

Most higher education institutions in Uganda are using some form of cloud service with private or on-premise cloud deployment models the most prevalent

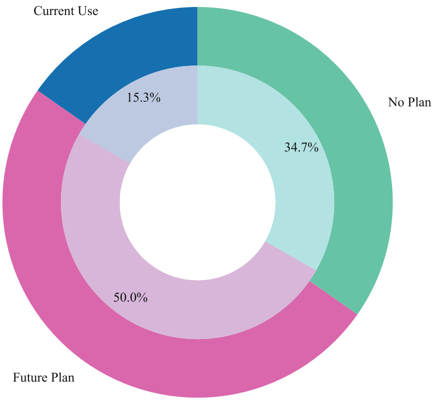

Fig. 1. The state of cloud-native in higher education institutions in Uganda: Less than 16% of the institutions are using any form of cloud-native technology and over 30% have no immediate or long-term plans.

(44.4%). 61.2% of the respondent institutions use a hybrid cloud (private, community and/or public) as supporting infrastructure for their services. On the public cloud, Google Cloud Platform (GCP) is widely used with 66.7% of the respondents with Microsoft Azure a distant third with 11.1%. The community cloud with 22.2% of the institutions is provided by the Government of Uganda and RENU. The main cloud service model used by institutions (83.3%) is Software as a Service (with example software applications including Google email, Google Apps for Education, Zoom, Learning Management Systems, CRM, ERP). Infrastructure as a Service (IaaS) - a form of cloud computing where a resource pool is provisioned as a virtual machine (VM) or instance with an operating system and optional prebuilt packages - closely follows at 72.2%. The VMs are either reserved or provided on-demand to run a set of workloads.

The study revealed that 46.2% of the participating higher education institutions in Uganda have incorporated cloud computing as a dedicated course unit within their undergraduate or graduate programmes. This inclusion is particularly prominent in disciplines such as Computer Science, Software Engineering, Information Technology, and Information Security. The subject content of these courses varies among institutions, but generally encompasses fundamental aspects of cloud computing. Despite the presence of cloud computing courses, research on cloud systems within these institutions is relatively limited. This can be attributed to the infrastructure constraints prevalent at the institutions. However, it is worth noting that research in other fields, such as Artificial Intelligence (AI), heavily rely on the infrastructure provided by cloud platforms. Integration of cloud computing into academic curricula highlights the recognition of its importance and the need to equip students with the necessary knowledge and skills in this evolving field. While research in cloud systems may be hindered by infrastructure access, the cloud requirements for computation-intensive operations in these settings are paramount.

5 Cloud Adoption Assessment for Higher Education Institutions

A cloud adoption assessment tool can help a HEI to track maturity and progress in adopting cloud technologies and supporting practices. The tool should use key indicators of the HEI domain to capture the current state of adoption of a technology. There are a number of maturity models and frameworks that have been developed [19,36,37] with differing levels of complexity, generalization and applicability. For a specific context, the generic models require significant amount of rework as the target is mainly the enterprise. There have also been advocacy efforts for a more holistic approach to developing a standardized adoption model from a consumer perspective [35]. However, the cloud has been dynamic with incorporation of new and advanced technologies, and a universal maturity model would most likely be obsolete within a few years of use. The assessment tool should also be contextual as domain differences exist, for example in computing resource concentration. Maturity models mostly define five stages of the adoption journey from none to extensive and optimized usage of cloud services. Nonetheless, we extend these stages analogized by planting practices in a tropical region dominated by the agricultural sector. The findings of the survey provide key inputs to the development of this tool as shown in Fig. 2.

1. ***Pre-season Stage:*** During the pre-season, which is marked by uncertainties in the agricultural cycle (weather, production costs, harvest, demand and eventual product prices), institutions face similar challenges in their cloud adoption journey. While they may possess basic knowledge of cloud computing, they are hampered by concerns about adoption and the potential challenges that lie ahead. As a result, there are no immediate or future plans to transition their services or infrastructure to a cloud-based solution. These institutions rely on on-premise infrastructure and predominantly utilize monolithic applications. In some cases, cloud adoption may be deemed irrelevant to their foreseeable needs.
2. ***Seed Stage:*** Akin to planting seeds in fertile soil (the odds are very much in favor of the farmer), this phase represents the initial stage of cloud adoption in institutions. They recognize the potential benefits of cloud technologies and begin to explore their capabilities. The opportunities presented by the cloud outweigh the adoption barriers they may face. Activities during this phase include conducting feasibility studies and researching cloud service providers to lay the foundation for future adoption. Institutions may also run experimental applications in the cloud to gain hands-on experience. Management becomes supportive of the cloud proposition, and there is a strategic direction for cloud adoption. The on-premise data center infrastructure undergoes virtualization (IaaS), resulting in improved utilization of available compute resources. To bridge the education and industry demands, cloud computing modules can be incorporated into the curriculum.
3. ***Sprout Stage:*** In the Sprout stage of cloud adoption, institutions witness the value of growth and development in their cloud adoption efforts. They

begin migrating critical workloads to the cloud, leveraging the benefits it offers. Technical personnel acquire the necessary skills to effectively manage and administer cloud resources, ensuring smooth operations. To overcome local power challenges and enhance availability, institutions take advantage of collocation services, which provide reliable infrastructure and minimize disruptions. Additionally, some institutions make substantial investments in setting up local cloud infrastructure, tailoring the cloud environment to their specific needs. The students learn how to develop applications that can leverage cloud service models, enabling them to experience the power of the cloud.

4. ***Mature Stage:*** The institutions have established strong roots, much like a mature and thriving plant in the African environment. They have achieved a high level of maturity in their cloud adoption journey, encompassing various aspects of cloud technology. Institutions widely utilize cloud deployments, embracing the flexibility and scalability they offer. They adopt cloud-native architectures, leveraging microservices, containers, and serverless computing to build resilient and agile systems. Governance frameworks are in place to ensure compliance and security measures are enhanced to protect data and systems. For on-premise clouds, the infrastructure is distributed, enabling efficient resource allocation and workload management. Disaster recovery and business continuity plans are documented and regularly tested to ensure their effectiveness in case of disruptions. The technical teams within institutions are more structured, with a strong focus on collaboration between Development (Dev) and Operations (Ops). DevOps principles and practices are ingrained in the institutional culture, promoting collaboration, automation, and continuous improvement. Overall, in the Mature stage, institutions have established robust cloud architectures, implemented governance frameworks, enhanced security measures, and embraced DevOps practices, enabling them to fully leverage the benefits of cloud technologies and drive innovation.
5. ***Harvest Stage:*** Like a bountiful harvest in an agricultural cycle, the institution has fully integrated cloud technologies into its ecosystem. This stage represents a mature and thriving cloud environment, characterized by several key aspects. Firstly, the institution has established strong cloud partnerships and collaborative relationships. It actively engages with other institutions, industry leaders, and cloud communities to share best practices and knowledge gained from its own experiences. This collaborative approach fosters a culture of continuous learning and improvement within the cloud community. Secondly, the institution has achieved optimized performance, scalability, and cost-efficiency controls in its cloud environment. It has fine-tuned its cloud infrastructure and processes to ensure optimal utilization of resources, seamless scalability to meet demand fluctuations, and cost optimization strategies to maximize value. Furthermore, the institution's contributions to the cloud community and its sharing of best practices are notable. Cloud providers recognize the institution's expertise and value its contributions. As a result, they may provide grants, credits, or other forms of support to further the institution's research and innovation in the field of cloud computing. The institution may drive advancements, influences industry trends, and contributes to

the overall growth and development of cloud technologies. Its expertise and thought leadership have a meaningful impact on shaping the future of cloud computing.

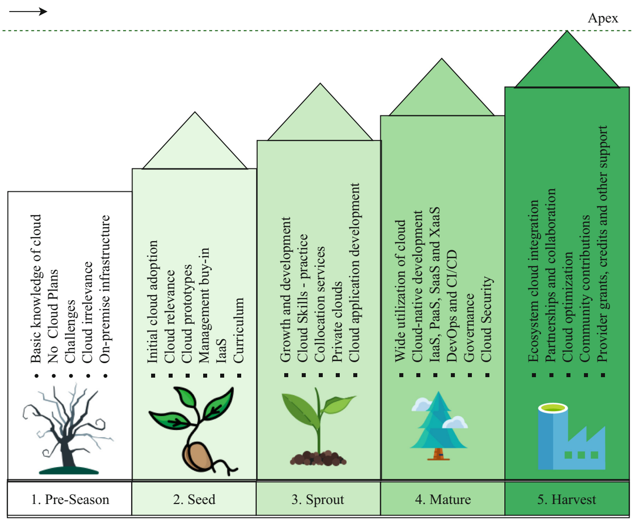

Fig. 2. A Cloud adoption assessment tool for higher education institutions in developing settings. In the pre-season, the institution has no cloud plans and the harvest phase involves the institution as part of the cloud ecosystem.

Based on the survey results from 26 higher education institutions in Uganda and using the phases defined in Sect. 5, the current state of these institutions can be determined. We develop an adoption matrix from Fig. 2 and generate the assessment of each institution and shown in Table 2. *I - Institution, CxxT - Institution Code (where xx is a numeric identifier and T is the institution type which is either G for public or R for private), P1 - institutional plans for cloud, P2 - business need for cloud, SE1 - institutional cloud prototypes, SE2 - relevance and support for next stage, SE3 - management support and involvement, SE4 - use of IaaS and/or SaaS and virtualization, SP1 - growth and development in the cloud, SP2 - real (production) application workloads on the cloud, SP3 - collocation and/or use private clouds, SP4 - research, teaching and learning in cloud computing, M1 - wide utilization of cloud technologies, M2 - the use of cloud-native and DevOps practices, M3 - demonstrated use of XaaS in the cloud, M4 - governance structures on cloud administration, H1 - Grants on use of cloud services, H2 - Optimized usage of cloud resources, H3 - community support in the use and development of cloud services, H4 - partnerships and collaborations with cloud providers.* The score range breakdown is as follows: Preseason (0 - 1), Seed (3 - 6), Sprout (7 - 10), Mature (11 - 14) and Harvest (15 - 18). The overall results are presented in Fig. 3.

Table 2. Cloud adoption assessment of HEI in Uganda

I	Pre		Seed				Sprout				Mature				Harvest				Total
	P1	P2	SE1	SE2	SE3	SE4	SP1	SP2	SP3	SP4	M1	M2	M3	M4	H1	H2	H3	H4	
C01G	1	1	1	1	1	1	1	0	0	0	–	–	–	–	–	–	–	–	**7**
C02G	0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**0**
C03G	1	1	1	1	1	1	1	0	0	0	–	–	–	–	–	–	–	–	**7**
C04G	1	1	1	1	1	1	1	1	0	0	–	–	–	–	–	–	–	–	**8**
C05G	1	1	1	1	1	0	–	–	–	–	–	–	–	–	–	–	–	–	**5**
C06G	1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**1**
C07G	1	1	1	1	1	1	1	1	1	1	1	1	0	0	–	–	–	–	**12**
C08G	1	1	1	1	1	1	1	1	1	1	1	1	0	0	–	–	–	–	**12**
C09G	1	1	1	0	0	0	–	–	–	–	–	–	–	–	–	–	–	–	**3**
C10G	1	1	1	1	1	1	1	1	1	1	1	1	0	0	–	–	–	–	**12**
C11G	1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**1**
C12G	1	1	1	1	1	0	–	–	–	–	–	–	–	–	–	–	–	–	**5**
C13R	1	1	1	1	1	1	1	1	0	0	–	–	–	–	–	–	–	–	**8**
C14R	1	1	1	1	1	1	1	1	0	0	–	–	–	–	–	–	–	–	**8**
C15R	1	1	1	0	0	0	–	–	–	–	–	–	–	–	–	–	–	–	**3**
C16R	1	1	1	1	1	1	1	1	1	0	–	–	–	–	–	–	–	–	**9**
C17R	1	1	1	1	1	1	1	0	0	0	–	–	–	–	–	–	–	–	**7**
C18R	1	1	1	1	1	1	1	0	0	0	–	–	–	–	–	–	–	–	**7**
C19R	1	1	1	1	0	0	–	–	–	–	–	–	–	–	–	–	–	–	**4**
C20R	1	1	1	1	0	0	–	–	–	–	–	–	–	–	–	–	–	–	**4**
C21R	1	1	1	1	1	1	1	1	1	1	1	1	1	0	–	–	–	–	**13**
C22R	1	1	1	0	0	0	–	–	–	–	–	–	–	–	–	–	–	–	**3**
C23R	1	1	1	1	1	1	1	0	0	0	–	–	–	–	–	–	–	–	**7**
C24R	1	1	1	1	0	0	–	–	–	–	–	–	–	–	–	–	–	–	**4**
C25G	0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**0**
C26R	1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**0**

The largest number of institutions (34.6%) are in the sprout stage, experiencing growth and development attributed to the use of cloud services, with real application workloads in the cloud, utilization of collocation services and private clouds, and potential involvement in cloud computing research. The next significant number of institutions (30.8%) are in the seed stage, having a business case supported by governance, at least one production service in the cloud, and relying on virtualized infrastructure. A smaller percentage of institutions are in the preseason (15.4%) and mature (11.5%) stages, with no institutions currently at the harvest stage or close to it, which represents an advanced level of maturity, with a symbiotic relationship with a cloud provider, actively monitoring and optimizing cloud operations for service delivery and cost efficiency.

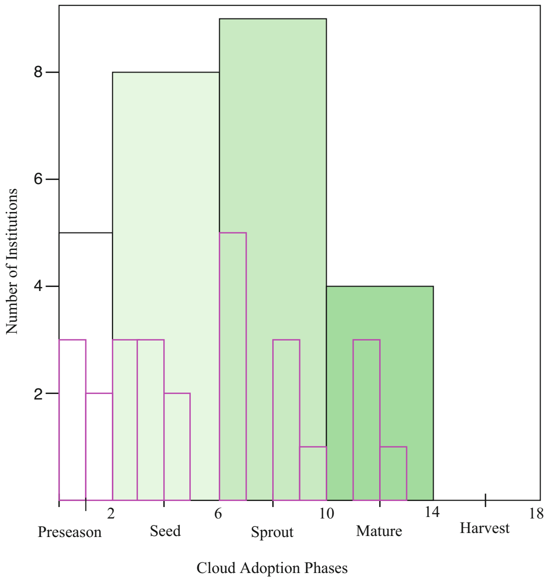

Fig. 3. The survey results of higher education institutions in Uganda in their cloud adoption journeys using the model in Sect. 5. The mini bar-plots represent the distribution of the institutions at each phase.

6 RQ4: Cloud Adoption Outlook

Cloud adoption in higher education institutions in developing economies is hindered by several challenges. The major inhibiting ones being the high costs associated with *cloud commitment* and concerns regarding data privacy, security and sovereignty. With the enactment and expected enforcement of data residence laws in many countries, institutions are cautious about large-scale migrations to the cloud. Compounding the problem is the sparse distribution of public cloud service providers in these settings, further limiting the options available. Additionally, network partitions can isolate institutions from cloud services due to unreliable local and upstream connectivity. The limited infrastructure in terms of bandwidth availability and high costs pose further challenges. There is a disconnect between service availability, connectivity, data center power and other operational issues and how the cloud can or should bridge the gap. The location of the consumers of a service can influence its placement at the cost of availability and quality of service. If there is a local connectivity challenge to a remote cloud service, then there is an availability challenge to the local users - this may not necessarily affect the remote users. If there is a local data center operational or system issue, there is still an availability challenge to both local and remote users (including multi-campus institutions). One approach that can be explored is in the federation of available compute infrastructure at the different institutions to create a diverse, more available and bigger edge-like resource pool. The institutions that desire to collaborate shall be expected to meet local connectivity requirements. Government nation-wide fiber expansion programmes and RENU campus interconnection can provide the federation network. Software abstractions to interface with this resource pool can be explored.

Despite the connectivity challenges in higher education institutions, there is indicative progress in adoption of cloud technologies. There is a pressing need for increased awareness and comprehensive training programs to cater users at various levels of expertise. Starting from the fundamentals, such as describing the relevance and benefits of cloud-based systems, to addressing concerns regarding security and other barriers, this approach will establish a solid foundation for widespread adoption. It is imperative for institutions to incorporate cloud computing into their curricula, allowing them to tackle research challenges specific to their local context and community in both the medium and long term. This requires playground infrastructure of a cloud provider available to staff and students to reinforce class sessions. Cloud providers offer discounted education pricing which is still high for users in these settings. Given budget constraints in developing economies, further discounts or *diversity* platforms should be explored. GÉANT[6], the pan-European data network for the research and education community, has negotiated over 400 framework agreements with commercial cloud providers with significant discounts to the higher education community in 40 European countries [7].

Cloud adoption by higher education institutions can influence efforts in other business domains. Initiatives focused on digitization encourage and urge organizations to prioritize the utilization of cloud computing services for their IT infrastructure and application deployment. This prioritization is aimed at enabling organizations across various sectors to harness the numerous advantages offered by cloud computing. In Uganda, the attainment of its Vision 2040 [11] is hinged on the use of ICT (and the cloud) [14] to power most development sectors for middle income status. The digital government strategy [12] under NITA-U considers *'aggregation of hardware and software across different government sectors'* as one of the objectives in the desired direction. However, the successful implementation of such agendas heavily relies on the availability of technical resource pools from the research and education sectors. These sectors play a critical role in providing the necessary expertise, knowledge sharing, and innovation required to support and drive the adoption of cloud technologies. Without adequate contributions from the research and education domains, the progress and success of these digitization agendas may be at risk.

6 https://geant.org/.

7 Conclusion

Cloud adoption in higher education institutions in low-resource settings is still in its early stages, despite the numerous benefits it offers, including availability, cost-efficiency, and resource scalability. In Uganda, the adoption of cloud services is seen as a double-edged sword, with most benefits overshadowed by a pessimistic perspective. Some question the relevance of cloud services for institutions that are already grappling with challenges related to local network connectivity and limited ICT budgets. As government strives to improve connectivity by investing in national backbone infrastructure, the rate of cloud adoption is expected to improve. The establishment of new tiered data centers in the country, such as Raxio and the Government National Data Center, will contribute to this progress and provide added value to the ecosystem. To promote a more holistic integration of cloud computing, it is essential to incorporate cloud-related topics into the institutional curriculum. This includes providing cloud training and raising awareness among stakeholders at various levels of expertise and responsibility. Considering the existing staffing gaps and technical limitations, development and use of abstractions that manage cloud infrastructure and services can offer a promising avenue for further research and exploration.

In the wider low resource context, a clear understanding of the current state of cloud adoption in HEIs can be useful. The cloud adoption assessment tool proposed in this paper can provide a baseline, but can be adapted where required. Whereas our case study focused on Uganda, the low compute resource definition extends to most countries or regions in developing economies. The properties of limited or unavailable cloud infrastructure, connectivity and data center power challenges and the skill-set required to develop and operate cloud-based solutions are not particular to Uganda. One of the recommendations that we highlight in the paper on local federation of available resources between institutions can provide an understanding of the ubiquity of cloud resources. In addition, this can ensure a better utilization of available resources especially for tasks that require scalable computing power. Governments, providers and other sectoral entities can play a role in adoption but we believe that the higher education sector can play an even integral role in the chain.

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