Contextualizing *micro* High Performance Computing Artifacts in Higher Education

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***Abstract*—The education system of Tanzania uses computing artifacts to support curricula. Computer science, as one of the fields of study, uses high-performance computing artifacts as a learning tool. However, there is a need for knowledge on designing an HPC artifact in the education context. In this study, we designed and deployed a micro HPC artifact, which is portable and used a credit-card-sized computer and the Linux operating system. The designing phase used the micro HPC artifact to gather knowledge and skills learned by students on how to improve the design. This paper aims to explain the processes of designing micro HPC artifacts as educational tools using the design science research methodology. In this study, we utilized focus groups to gather information regarding improving the design of micro HPC artifacts using the DSR paradigm. The design outcome of this paper can be used as a manual for improving the design of micro HPC artifacts for computer science education.**

Keywords— micro HPC artifact, HPC, focus group, design science research, HPC education, high-performance computing artifacts

I. Introduction

High-Performance Computing systems are important teaching tools that enhance and change how computer science education is delivered [4] [5]. However, access to High-Performance Computing (HPC) from classrooms and laboratories for students in developing countries has presented challenges due to the total cost of ownership associated with data-center-based HPC systems. This affects the delivery of computer science courses. However, the emergence of powerful credit-card-sized personal computers (PCs) has enabled the design of HPC systems that use a Beowulf architecture. These credit-card-sized PCs enable system integrators to build micro HPC (µHPC) clusters, which, apart from their scalability, efficiency, and availability, have a number of attributes that are not shared with conventional data-center-sized HPC clusters [1][2][3]. The HPC system combines off-the-shelf computing hardware and components such as processors, memory, data storage, communication and software, and parallelizes data movement at each possible process in order to achieve higher computation speeds [15]. Building the HPC cluster has often required the use of bulky and expensive off-the-shelf computing hardware and components. The small form factor and low cost for computing hardware and components have made the implementation of the HPC cluster simple and cost-effective. Clusters with these attributes can be improved to enable them to be used as educational tools that support computer science curricula.

In this study, we intend to improve our µHPC system by studying the experience of actual users. As indicated in [6], when embarking on building artifacts, one needs to design the actual artifact using design science. According to the suggestion of Gregor and Hevner [12], design science research (DSR) contributions can be classified as improving real-life situations (new solutions for known problems), inventions (new solutions for new problems), routine designs (known solutions for known problems) and exaptations (known solutions for new problems) of solutions to a problem. We study the improvements to our µHPC system as an educational artifact from the viewpoint of students who use the artifact. The choice of DSR as a method is based on its intrinsic characteristics of supporting the designing and evaluation of artifacts [8]. The validation should demonstrate the accomplishment of all stipulated functions of the artifact [10], as this will ensure the applicability of the research. Moreover, the validation of aesthetics of the artifact determines the beauty, which affects the usability of the artifact [41][42]. Similarly, as explained in [7], the redesigned artifact should follow the processes that describe the purpose of the design of the µHPC system, the character of the system, and the education environment in which the system will be applied.

The purpose of this study was to redesign an artifact in the form of improvement to the existing µHPC artifact by utilizing DSR. The new µHPC artifact will help students in resource-constrained environments to overcome the challenge of accessibility and affordability of HPC systems in a computer science education context. The design of the artifact involved students who used the artifact in the educational context in Tanzania. The research problem is to improve parallel computing education by redesigning a µHPC cluster that reduces affordability and accessibility challenges to help computer science students in Tanzania learn how to build, configure, program, and apply the HPC cluster.

Thus, the initial general objective of our study is to provide insight into refining the functional requirements, non-functional requirements, and the design of µHPC clusters in the education context. The non-functional requirements are general qualities that do not address the functionality of the artifact but instead address issues such as usability, portability, affordability, aesthetics, and learnability. The specific objectives were:

- To identify the functions, non-functional requirements, and inner components of the µHPC cluster that need to be improved;
- To develop the improved µHPC system;
- To explore the usage of mobile computing devices as computing nodes of the µHPC system.

The main research question addressed in this study is: How to contextualize a µHPC artifact that satisfies **affordability** and **accessibility** so that students in Tanzania can build, configure, program, and apply µHPC clusters in a computer science education context?

In this study, contextualization is the process of gaining insight from the experience of actual users of the artifact to improve the design. Affordability means making the µHPC system relevant and cost-effective to students in rural areas. Finally, accessibility means making the µHPC system readily available without limitations to those students. In order to address the main research question, we investigated the following research sub-questions:

- What improvements does a user perceive to be needed in the functions and inner components of the µHPC cluster?
- How can the non-functional requirements of the µHPC cluster be improved?
- How could mobile devices be used as computing nodes for the µHPC cluster?

This study employs confirmatory focus groups (CFGs) in the DSR method based on design science cycles [11]. CFGs were employed to incrementally refine the design of µHPC clusters as the education artifact. Participants took part in the focus groups to design a µHPC cluster that is ideally suited to support curricula in computer science. As the CFG methodology was used to obtain data, the design of µHPC clusters could be incrementally refined to design low-cost entry-level HPC systems. The redesigned low-cost entry-level HPC system is expected to inspire and enable students to build, configure, program, and apply HPC to tackle complex computationally demanding challenges. The affordable and accessible µHPC cluster can enable students in developing countries to overcome the challenge of access to HPC facilities and enable them to practice "hands-on" in the education context.

II. METHODOLOGY

The section provides an overview of the research methodology used in this study. The other parts provide a reflection on the research processes that have been employed, and the participants that took part in the study are described. Finally, the data collection and data analysis approaches used in this study are articulated.

A. *Research Method*

The published literature on HPC has shown limitations in covering the experience of contextualizing HPC systems in the academic environment. This study is a step toward solving this limitation by designing HPC based on the feedback of students who worked with µHPC systems in educational settings. The study captures realistic usage experiences from students in order to improve the design of µHPC. In order to address the research questions of the study, qualitative research was adopted to refine the HPC artifact's design from users' reflections in the DSR paradigm. In exploring users' reflections and perspectives using qualitative research, investigators are able to readdress old questions, answer different kinds of questions, and ask new questions [39].

DSR is a research paradigm that guides the building and evaluation of novel artifacts, and since DSR is both a process and product [25], we intend to use it to guide the study in collecting evidence as feedback from users on whether the artifact solved the class of problem that it was designed for. In DSR, feedback from users is an essential component for the improvement of the design of the artifact [30][31][32], and in line with that, we chose focus groups to guide our study. Contrary to quantitative studies, a focus group study provides rich interaction and input feedback among participants related to a topic of interest [35], flexibility in a discussion about design topic and domain, and building on others' comments in the focus group [22]. The study utilized a confirmatory focus group as the research paradigm in the DSR framework to change the HPC artifact [17][18]. We adopted Tremble et al.'s model that integrated focus groups in DSR [19] to guide this study. The aim of using a confirmatory focus group is to study the information from the feedback of participants' interactions after the experience of using the artifact [20] in the application environment, in this case, the µHPC artifact. The essential component of DSR is the feedback information that can contribute to improving the artifact's design [23]. The generated information is studied to demonstrate the utility of the HPC artifacts in the education context [17]. Hence this methodology allows feedback to refine and evaluate the designed artifact [19][21].

We used thematic analysis templates as the data analysis method to analyze transcribed data in order to enhance validity and prioritize topics [14][40]. Due to its swiftness and flexibility, thematic analysis is used to identify themes, patterns, and interpretations in data [14][29].

B. *Design of the Study*

The approaches used in this study are qualitative [16]. The appropriateness of a qualitative approach in this study is grounded on the research objective that focuses on discovering participants' details of their user experiences and the contextual issues of the interactions between µHPC and the participants [27]. The researchers were the primary tool of data collection in the qualitative study. The focus of the qualitative approach was to gain insight that will enable understanding the improvements of the design of the µHPC system from the user perspective, and the exploratory focus group was employed to receive the feedback for refinement of the µHPC system.

C. *Sample Selection*

Random sampling was used to select participants from the pool of participants who designed and used the µHPC system. The purpose of that was to gain timely and critical insight into their experience of using µHPC. We sought diversity in the sample to allow wider feedback that enabled the contextualization of the µHPC system. The research took place within a department in a higher education institution in Tanzania. The institution was selected because of the availability of datacenter-sized HPC, the location of the µHPC training, and the presence of a curriculum that includes HPC. We conducted two focus groups from participants who were recruited from the institution. The participants were homogeneous in terms of knowledge of the µHPC system of which encouraged members of focus groups to participate equally. All participants had knowledge of the µHPC system before focus group sessions were conducted. The participants performed the task of designing a µHPC system using a Beowulf Architecture. Some other tasks were to apply networking principles to connect components of the µHPC system. Some tasks focused on configuring system components of the μHPC system, others on the use of the operating system (OS) to manage parallel applications. Some tasks involved writing parallel codes using the μHPC system, and others benchmarking the performance of the system.

1) *Participants:* We invited 12 participants from the institution, of whom eight voluntarily showed up. All eight participants were male and familiar with the μHPC system. There were four participants from degree courses and four from diploma courses. Participants were approached from the list of students enrolled in the HPC course. We kept the group of participants as similar as possible in terms of their participation in the design of the μHPC system. As indicated in [28] because having differences in experts' perspectives and backgrounds may lead to differences in the processes and the outcome. Moreover, bringing together participants with too diverse backgrounds in relation to the topic of interest could result in data with shallow depth [24]. According to Morgan [33], the focus group should have a minimum of 4 participants and a maximum of 12. To ensure that the participants had different points of view about the μHPC system, the group had at least 2 participants from diploma courses and 2 participants from degree courses. According to the education system of Tanzania, diploma courses run for three years which are for students who have finished secondary school. Degree courses admit students who have successful, accomplished diploma courses or A-Level school. We used two rounds of focus groups in this study to gain insight into the issues that can be used to redesign the μHPC system.

2) *Pilot Study:* A total of two focus groups were conducted. The first was a pilot focus group comprising four participants to help understand the questioning route, evaluate the moderator style, any logistic issues, and issues of timing. Using a pilot focus group is recommended [18][26] in order to articulate the setting of the focus group. The focus group session took place in an office at the institution. In the analysis phase, the data from the pilot study were not used.

3) *Questioning Route:* We developed a flexible pre-defined open-ended questioning route that corresponded to our research objectives for this focus group study. The questions aided the moderator in keeping the discussion on the topic of the research by giving him the freedom to address emerging questions and issues during the focus group sessions. The questions were designed (developed and pre-tested) in a way that not to be suggestive of the expected outcome, and stand-alone open-ended questions pertaining to a wide range of experiences of using the μHPC system were asked. We ensured that the number of questions numbered below 12 as our focus group was planned to last not more than 2 hours [34].

The participants were asked questions that covered six specific and independent interview topics: "Properties of the redesigned mobile HPC cluster"; "Impressions toward the μHPC system"; "Desired properties of the μHPC cluster"; "Specific properties of the μHPC system that should be in a mobile HPC system"; and "Things that you like and dislike about the μHPC system." In the area of "Properties of the redesigned mobile HPC cluster," the questions asked to participants were about the properties of any HPC system, the support for programming languages, and the expected properties of the designed mobile HPC cluster.

In the area of "Desired properties of the μHPC cluster," the questions asked to participants were about the properties that they would like, based on their experience of using the system; the improvements participants would like to see in the μHPC system; their satisfaction with the system; the desired properties of the system made up with mobile phones as computing nodes; the application of the mobile μHPC system in the education context; configuration of the mobile μHPC system; usage of the Linux OS; and the possible usage of a mobile μHPC system that supports Linux OS in education.

In the area of "Things that participants like and dislike about the μHPC system," the questions asked to participants were about things that participants like and dislike about the μHPC system; and any additional comments on the μHPC system. We informed the participants that these are important comments, but if no constructive comments come to mind, they shouldn't comment as the questions were an option. This was done to avoid meaningless comments.

4) *Moderator:* The moderator provided general information on general rules, the objective of the focus group, and the timeline in the short introductory presentation. The role of the moderator included keeping the discussion on topics of the research and focusing the discussions [22]. We selected a moderator who had the respect of the participants, the best communication skills, ability to listen, and self-discipline to control his own view and knowledge of the HPC system. We chose a moderator who was one of the designers of the μHPC system and a lecturer of HPC that had used the μHPC system. The moderator conducted both focus group sessions. The moderator was the primary researcher, and another researcher was the observer to take notes and help in timekeeping during the session. The recording equipment was tested beforehand.

D. *Research Bias and Assumption*

To ensure that sunk cost bias, anchor bias, and confirmation bias were avoided during focus group discussion, we encouraged making decisions in the group when different views on the same topic were expressed by participants. The consent was obtained by orally reading their rights, limits of confidentiality in the focus group, and the objective of the study, including the rights to withdraw from the study at any moment during the study as their involvement is voluntary. In order to avoid the bias of participation, no payments were made to participants. No participant withdrew from the study. The oral request for permission to record the group discussion was sought and granted by all participants for traceability purposes. In order to comply with the ethical standards of the DSR, the information of the participants has been kept confidential by addressing them as participants; hence the guarantee of anonymity was observed. The quotations, categories, and sub-categories were reviewed to avoid researcher bias.

E. *Data Collection, Coding Processes, and Data Analysis*

The participants used the μHPC system to perform a number of activities during the implemented HPC course. The focus group was facilitated by one of the authors, who acted as a primary investigator and was assisted by two facilitators. One was doing the audio recording, and the other was writing the notes and assisted with the flow of the conversation. We held one session for each group. The first session lasted about 30 minutes. The second lasted around 45 minutes which is less than the planned two hours. All sessions were conducted in one day in English. Participants received refreshments during focus groups.

We verified the transcript against the recorded audio. In this study, the dataset consisted of focus group data, which was transcribed verbatim. We managed and organized focus group data using word processing software. The main steps of thematic analysis templates were adhered to by the researchers. We interweaved data analysis and data collection concurrently to help to cycle back and forth between thinking of existing collected qualitative data and generating strategies for collecting new, better qualitative data. We developed templates based on our experience in researching and teaching the HPC system. The template was renamed as sub-categories in Table 1. Two researchers carried out the thematic analysis templates manually and independently categories until consensus was reached.

TABLE I. THEMES, CATEGORIES, AND SUB-CATEGORIES FOR CONCEPTUALISATION OF MICRO HPC SYSTEM.

No.	Theme	Categories	Sub-Categories
1.	Improvement of the functions and inner components of the µHPC cluster	Improving the integration of components	Integration
		Improving the system architecture	Clock rates
			Number of processors
			Storage
			Form factor of HPC
			Power
		Software support	Benchmarking
			Operating system
			HPC software packages
		Support for parallel programming	Parallel programming
		Improving inter-system communication	Networking
			Wireless network
2.	Improvements of non-functional requirements of the µHPC system	Improving the usability of the system	Portability
			Affordability
			Aesthetics
			Adaptability
			Ease of use
			Scalability
			Programmability
			Ease to configure
			Ease to learn
			Transferability of knowledge and skills
3.	Usage of mobile devices used as computing nodes for µHPC system	Support for mobile phones as computing nodes	Mobile computing devices

Though analysis and coding are different processes, coding is still an important aspect of analysis [43]. We used NVivo software to code the focus group transcript data and to derive themes, categories, and sub-categories. This made the coding process top-down. The criteria for inclusion of participants' statements into sub-categories were based on the clarity of expression, relevance to the research questions, and consistency with other included statements. The categories that were used to contextualize µHPC were: improving the integration of components, improving the system architecture; software support; support for parallel programming; improving inter-system communication; improving the usability of the system, and support for mobile phones as computing nodes (see Table 1).

F. *Validity and Reliability*

The evaluation of an artifact in DSR establishes the validity of the research [9]. The design of the artifact is based on pragmatic validity [13]. In keeping to the constructivist worldview, we ensured the trustworthiness and authenticity of the study by designing measures that focused on methodological rigour. Focus group weaknesses that can possibly pose a threat to the validity of the study are hidden agendas, group dynamics, social susceptibility, and limited comprehension [38]. As for limited comprehension, we selected participants who used µHPC in the HPC training. For social susceptibility, we ensured that the moderator stated ground rules for focus group discussion, and the moderator drove the discussion.

We also ensured the moderator of the sessions was not one of the designers of the research method, and research artifact as biases associated with the researcher could be present either during focus group sessions, planning, or analysis [36]. We used investigator triangulation as a strategy to ensure the trustworthiness and authenticity of this qualitative study. We also used the strategy of respondent validation to ensure that emerging findings from qualitative data are clarified by some of the people we interviewed. This helped to identify researcher biases and misunderstandings in the observed issues [37]. We ensured the trustworthiness of the data by providing recorded and written summaries of their responses in order to give opportunities for verification, clarification, and correction. This ensured that the findings were faithful and credible to the experience of participants.

III. RESULTS

In total, 8 participants attended the focus group. The results reflect the opinion of the majority of participants in the focus group. Repeated themes, themes of long discussions, initially raised themes, or strong feelings were given greater emphasis in the thematic analysis. We have highlighted differing opinions, perceptions, or experiences of participants in the group regarding the µHPC system.

Key functions and inner components of the µHPC cluster that can be considered in the contextualization of the µHPC system included the integration of components, the system architecture; software support; support for parallel programming; and inter-system communication. The key issues in regards to improvements of non-functional requirements of the system that can be considered in the contextualization of the µHPC system included the usability attributes of the µHPC system. The key issues in regard to the usage of mobile devices used as computing nodes for the system that can be considered in the contextualization of the µHPC system included the support for mobile phones as computing nodes.

In this study, the main findings are divided into three sub-sections. The first sub-section addresses the needed improvement in terms of the functions and inner components of the µHPC cluster. The second sub-section discusses the improvements in terms of non-functional requirements of µHPC. The third sub-section address the usage of mobile devices used as computing nodes for µHPC.

A. *Improvement of the Functions and Inner Components of the µHPC Cluster*

1) Improve µHPC System Architecture

According to focus group participants, the µHPC system should perform at the highest speed and high bandwidth; the processing components should contain multicores, and the power consumption should be low. One participant who faced challenging experience working with the µHPC system indicated the issue of power supply to the nodes because of an outage caused by the usage of power distribution USB hub. The participant explained: "*We discovered that the power distribution USB hub was not able to supply enough power that is needed to sustain and run computing-intensive applications like the Linpack Benchmarking application*."

The participant went further to explain the capability of a multi-plug adapter to consistently supply the amount of voltage required to run computing nodes is required. In addition, the proper functioning of the power adapter can improve the capacity of the µHPC system to handle different parallel applications. The focus group participants indicated that when designing the µHPC system, the design process should include the integration of a power adapter that will be able to supply electricity to two nodes, and the power must be able to scale with the increased number of nodes.

In the case of the storage attributes of the µHPC system, participants mentioned that the system should have a larger storage capacity. One participant stressed that the minimum storage capacity should be at least 10 GB for the computing nodes. All participants were impressed by its form factor and simplicity in working with the system's components. One participant mentioned liking the use of the credit card-sized processor board (Raspberry Pi) in building the µHPC system: "*For me, I was impressed by the form factor of the µHPC because initially, I thought any computers should have, at minimum, the size of the PC. So the size of the computing nodes and master nodes of Raspberry Pi was a bit of a surprise for me*".

The mention of form factors such as the size of the µHPC system and its portability showed a good impression of another participant towards the system. The participant initially thought that a supercomputer could occupy a big room and require a special type of networking solution, but working with µHPC changed his previous perception of a supercomputer as it was smaller in size. The size of a computing node made of Raspberry Pi was small, contrary to his belief that it should be of the size of a personal computer.

2) Software Support

The participants mentioned that the µHPC system should run the OS that supports the parallel application software, e.g., the Linpack software. The participants also suggested that the µHPC system should be optimized to run lightweight software packages and benchmarking software packages based on the Linpack software. One participant remarked about the benchmarking as follows: "*I liked the knowledge and skills of benchmarking the HPC system.*"

When it came to the OS, participants mentioned that each node should be able to run or support Linux. The participants expressed satisfaction with the support for the Linux OS and the experience of working with Linux using the µHPC system. Another participant was impressed by the affordability factor as the µHPC system supported open-source software packages that are freely available. One participant expressed interest in using Linux commands: "*The configuration of the cluster using Linux command was very interesting.*"

The participants mentioned liking the simplicity of working with the Linux OS. This was attested by one participant, who initially was familiar with Microsoft Windows OS, who was able to move to work confidently with Linux on the µHPC system. However, one participant mentioned finding working in the Linux OS environment to be complex compared to the OS that he was familiar with before.

With regard to libraries, the participants stressed the necessity of overcoming the challenges of finding the libraries and software packages that support the µHPC system. The participant suggested that all necessary libraries and software packages should be put together in the images in order to assist during the installation of the µHPC system.

3) Improve Inter-System Communication

The participants initially thought that a supercomputer could occupy a big room and require a special type of networking solution, but working with µHPC changed their previous perceptions of a supercomputer as it was small. The participants went further to explain that the computing boards should support networking compatible with the available switches. One participant remarked: "*It made me understand the concept of networking and computer architecture.*" Five participants proposed the utilization of wireless networking for inter-node communication. This will enable nodes to be distributed in different geographic areas. The HPC should have high-speed wireless connectivity and network support. Another participant suggested that the mobile HPC cluster could overcome those difficulties as it uses a wireless network to connect computing nodes. Participants agreed that the mobile HPC cluster should use wireless networking to connect the master nodes and computing nodes.

4) Improve the Integration of Components

The participants mentioned the importance of non-functional components to the redesign of µHPC, such as the integration of keyboard and monitors in one portable package. One participant went further to propose: "*The µHPC clusters can be packaged on the size of 2 nodes, five nodes, eight nodes, and more, that are packaged with adapters and other relevant devices.*"

For that purpose, the integration of all components in a single system will enable the deployment of the system in rural areas. Moreover, the mobility of the µHPC system was mentioned to be one of the attributes to be considered in the redesigning process.

5) Support for Parallel Programming

In support of parallel programming languages, the participants mentioned that the µHPC system should support parallel programming. The focus group demonstrated consensus by stating that the improvement should be in support of a wide range of available parallel programming languages. The participants drew from their experience of the HPC course, which exposed them to the FORTRAN and Python programming languages. In line with that, participants said that the more support of parallel programming languages, the better. The participants also mentioned the designed µHPC system should use familiar programming languages to program in the parallel programming environment.

B. Improvements to the Non-Functional Requirements of the µHPC System

1) Improving the Usability of the µHPC System

The participants mentioned that the HPC cluster should be portable. One of them mentioned that form factors such as the size of the system and attributes of portability impressed him about the system. Another participant mentioned liking the portability of the system as the participant was familiar with the portability attributes of laptops. Another participant was impressed by the affordability factor because the hardware components and software packages are affordable and available in open source. The importance of affordability of the µHPC system was complemented by another participant who mentioned the cost and the non-functional factor, such as how µHPC system looks, are factors that contribute to acceptability to users: "*The cost of assembling the cluster is low, and the look of the µHPC is appealing. Also, the support of the Linux OS and working with Linux was good. The configuration of the cluster using Linux commands was very interesting*."

Participants mentioned liking the affordability and portability of the µHPC system as the participants were familiar with laptops. The factor of affordability was stressed by another participant who mentioned the cost, the non-functional factor of aesthetics of µHPC as the factors that interested him. Moreover, the participants proposed the protective cover case of the µHPC system of which should be strong. The cover case will protect the inner components of the µHPC system from accidents. Since as it is has been designed, the µHPC system is bare bone.

The participants were impressed by the network technology used to connect the computing nodes and the master node. They mentioned that the technology used in the HPC was similar to the networking technology they studied in their computer science curriculum. The µHPC system has enabled one participant who was initially familiar with the Microsoft Windows OS to work confidently with the µHPC system using the Linux OS. The participant showed that µHPC could be used as an educational tool to transfer the skills and knowledge required to operate a new Linux OS.

The scalability in terms of the number of ports was mentioned by participants to be key attributes in the redesigned µHPC system. Another participant commented that: "*The scalability of nodes is the key property that µHPC should have as there are other computing boards with more cores and high performance.*"

The participants mentioned that the support for many parallel programming languages is important when designing the µHPC system. So the programmability of the µHPC system should be considered in designing the system. One participant mentioned: "*I like the knowledge that I gained in parallel programming, of which I didn't know.*"

The participants mentioned liking the flexibility in configuring the µHPC cluster, troubleshooting problems, installing dependencies, and learning security for the cluster. Another participant mentioned liking the process of creating images of the computing nodes. The participant went further to mention that the image of the node made the task of installation of nodes and configuration very easy. The participants mentioned how easy it was to learn HPC concepts using the µHPC system. One participant commented that the µHPC system enabled him to learn the knowledge and skills required to use supercomputing, parallel programming, optimization of the µHPC cluster, and benchmarking the HPC system, something that he didn't think he would have been able to learn.

The participants also liked what they learned about how the performance of the cluster is influenced by random access memory (RAM) and system buses of the processor. They gained knowledge of how to choose hardware based on the required performance. Hence they mentioned learning about the criteria that are needed to be considered when choosing nodes of the HPC cluster. Other participants were impressed by its size and the simplicity of working with components of µHPC. One went further to say that: "*I realized that even people of diploma level could study and understand HPC. It made me understand the concepts of networking and computer architecture.*"

The participants also learned that a node could be desktop or laptop, so the knowledge gained from working with µHPC systems is transferable to other clusters of PC and laptops.

C. Use of Mobile Devices as Computing Nodes for the µHPC System

1) Support for Mobile Phones as Computing Nodes

The interviewees mentioned that compatibility of the devices when designing HPC using smartphones and other computing device is crucial. The participants indicated that the designed µHPC cluster should support or have the capability of networking with other devices. One participant mentioned: "*It should have enough memory as many mobile devices, e.g., smartphones have limited memory and storage memory*."

One participant mentioned that the consumption of power should be less as mobile devices have the limitation of batteries. This will enable one to run or execute applications that take time to complete without worrying about batteries. Another participant complemented the issue of battery life of computing nodes using a smartphone by mentioning that: "*Also during configuration, there are some processes that take time. So, battery life is crucial.*" Another participant mentioned the issue of the cooling system of the mobile computing node of cluster needing to be good: "*The smartphone has a tendency of heating up as one uses high computing applications. So there should be a good heating* *and cooling system for the cluster.*" Other participants went further to explain the possible usage for education purposes and using smartphones as computing nodes is more advanced than the µHPC system that uses credit card-sized personal computers. Participants considered that the smartphone, as a computing node, should have the capability not only to support a wireless network but also a wired network for applications that demand high network speed.

Participants mentioned the inherent challenge of finding smartphones that support Linux as many available smartphones support the Android OS. Even though Android is essentially Linux, but the issue is the support of parallel libraries. The participants attest this that the use of Android brings difficulty in finding supporting parallel libraries, software, and application that can be ported to a mobile HPC system.

There were mixed responses by participants regarding whether the Android OS could be better used as an OS in the HPC system, but most HPC systems use Linux as an OS and run Linux-supported parallel software packages. At the same time, another participant was of the opinion that there are not enough libraries and software packages of HPC that run in the Android OS. One participant said the computing nodes and master nodes should share the same file system and should have the same computing capacity. The other participant mentioned that a computing node made of Raspberry Pi has features to connect sensors and other devices, so the smartphone should also have that capability. Therefore smartphones should have the capability to connect to other external devices. The support of the Linux OS and of physical networks from regular wireless switches, was mentioned by another participant. Another participant explained the portability and transferability of the mobile HPC system in rural areas: "*It can be transferred in rural areas as the spread of smartphones in rural areas is higher.*" The design of a mobile HPC cluster should be adaptable, and the computing nodes should be able to provide dual functions: the mobile phone and the computing nodes.

Moreover, participants expressed that it is better to continue to use the same OS as the one they used when learning HPC using the µHPC system. The other condition is the use of a similar parallel programming language that they are familiar with. Familiarity with the OS and programming language was pointed as a key in the adoption of the mobile HPC system. Moreover, as an educational tool, the mobile HPC system should be able to support the transferability of the skills and knowledge acquired from using the µHPC system.

There were contradictions when participants were asked whether they will support a mobile HPC system that uses the Linux OS as an educational tool. One participant suggested that the use of smartphones that support Linux as computing nodes in the mobile HPC system will enable the transferability of knowledge gained from learning using the µHPC system. In contrast, another participant suggested that it will be better to use Android, as many people are familiar with the Android OS in smartphones. Mixed responses were given by other participants that Android could be better, but most of the HPC systems are using Linux as an OS and are running Linux-supported software packages. At the same time, another participant was of the opinion that there are not enough libraries and software packages for HPC that run in Android.

IV. DISCUSSION

The purpose of this study was to examine reflections as described by the experience of actual users of the HPC artifact about the contextualization of a µHPC system in Tanzania. According to the results of the study, the reflections on the µHPC system showed needed improvements in terms of integrated components, system architecture, supported software, supported parallel programming, inter-system communication; usability of the system; and computing nodes using mobile phones. However, the results satisfy the affordability and accessibility required by students in rural Tanzania to use the artifact to build, configure, program, and apply µHPC clusters in the computer science education context.

As reported earlier, the data analysis evidence shows the following.

A. *Improvement of the functions and inner components of the µHPC cluster*

Regarding the improvement of the functions and inner components of the µHPC cluster, we found that the designed µHPC system should be able to do the following.

- Integrate the off-the-shelf components needed in the HPC. The master and computing nodes should have the same computing capacity and the same file system.
- Use multicore processors that are able to provide high performance with low power consumption. This can be achieved by exploiting processing units that are able to work at a high clock rate at the same time consuming low power and overclock once that is needed.
- Use credit-card sized computing boards as computing nodes with high storage and high operating memory.
- Use power adapters that can supply the required power to the computing nodes and the master node that use low power consuming processors in order to manage power.
- Be optimized to run benchmarking software packages, including the Linpack software.
- Be designed with small form factor that is easy to carry.
- Support the open-source OS, Linux, is crucial for the affordability of the designed HPC system.
- Run image software of the system that includes the libraries and supporting parallel software packages.
- Support various parallel programming languages.
- Support physical and wireless networking technology protocols.

B. *Improvements of non-functional requirements of µHPC system*

With regarding improvements of non-functional requirements, we found the following.

- The attributes of portability, affordability, and scalability are crucial in the design of the system. The affordability can be achieved by exploiting cost-effective hardware and freely available open-source software. Scalability is key in designing the system in terms of the number of computing nodes and the processing units.

- The design should consider the protective case to protect the µHPC artifact from dust and other external accidents, e.g., spilling water on the circuit boards.
- The designed system should be easy to use in terms of running parallel programming, optimizing the cluster, and benchmarking the system.
- The designed system should be able to use the same network technology, open-source OS, and processors to increase adaptability for students.
- The use of Linux-based smartphones will enable the transferability of knowledge gained from using the µHPC system.
- The system should be designed in such a way that it is easier to learn how to configure the cluster, troubleshoot problems, install dependencies, and secure the cluster. The design of the system should consider the support of different parallel programming languages.
- The issue of the configuration of the master node and computing nodes can be made easier by the creation of image files of the system.
- The system, as the learning platform, should enable learners who are familiar with Microsoft Windows to confidently transit to work in the Linux OS environment and assist learners who are familiar with serial programming languages to learn parallel programming.

C. *Use of mobile devices used as computing nodes for the µHPC system*

Regarding the use of mobile devices used as computing nodes, we found the following.

- The designed mobile HPC system should be integrated with devices that are compatible with other computing devices.
- The portability and transferability attributes of the mobile HPC system will be useful in rural areas. The smartphone computing node should adapt to the deployed environment and provide dual functions, i.e., mobile phone and computing node.
- The mobile HPC system should use the same OS as the ones used in the µHPC system. The usage of a mobile HPC system that uses Linux-based smartphones as computing nodes will have more benefits to students in the education context compared to the µHPC system that uses credit card-sized personal computers.
- The smartphone as a computing node should overcome the inherent limitation of operating memory and storage memory.
- The power consumption and cooling of the smartphone should be kept at a minimum as mobile devices have the limitation of battery power. Lower battery life might affect applications that take time to execute.

D. *Critical points*

The critical points found in the process of contextualizing µHPC clusters are: the role played by a power adapter to power all the computing nodes in the µHPC system; the role of battery life of smartphones that are used as computing nodes; and the challenge of finding Linux-based smartphones that support parallel libraries, software and parallel application that can be ported to a mobile HPC system. Then the other critical points are: the challenge of finding enough HPC parallel libraries and software packages that can be ported to smartphones that run the Android OS; the slowness of the process of configuration due to slowness of the Internet, as most of the dependencies, had to be downloaded from the Internet; and the cumbersome package of the design of the µHPC since the monitor and other devices were separate components that needed to be handled separately.

Other critical points are: the time required to learn the skills and knowledge needed to work with the µHPC system; the need for patience in learning the system and the prior knowledge of Linux is crucial since some found Linux to be a complex OS as they used to work with other OSs. Also, the backup power is crucial for the availability of the µHPC system once the power supply to the system has been interrupted due to the electricity supply fails.

Further critical points are: the use of appealing and protective cases, as participants disliked the lack of case covers for the system; difficulties in the management of cables when adding computing nodes to the cluster and the possible usage of wireless networks to connect computing nodes; and finally use of offline mode to configure and install the µHPC system using the pre-downloaded libraries.

V. CONCLUSION

In order to contextualize the µHPC artifact, greater consideration should be given to the affordability and accessibility so that students in Tanzania can build, configure, program, and apply the µHPC cluster in a computer science education context.

The important implications of the results of this study are in HPC education in rural settings. We found that the most significant contribution of the study is that it is possible to improve the µHPC artifact in order to satisfy the affordability and accessibility to students in Tanzania. The study reveals a possibility of using a mobile HPC system that leverages smartphones as computing nodes in the education context. This will have implications in rural areas as the functions and inner components of the µHPC system can be optimized to overcome the challenges of those rural areas. The improvements in the non-functional requirements of a µHPC system will increase the usability of HPC artifacts. Therefore µHPC systems and mobile HPC systems can be used as educational tools to build, configure, program, and apply HPC systems for the benefit of computer science students.

This research study has several limitations to the validity and generalizability of the conclusion that deserves to be discussed. First, the contextualization of the µHPC system was exercised in an academic institution with a small sample size of students. The data cannot be transferable to other academic institutions since it wasn’t a multi-institutional study. The other limitation of the study is that the participants didn’t work on the actual artifact of the mobile HPC system.

Despite the limitations, this study has laid a foundation for future research into HPC systems to be built with smartphones in developing countries. At the same time, future research should include a mixed-method research design that studies the experience of students in the usage of HPC clusters built by smartphones. Future research should further explore the intervention of the HPC cluster that is made up of smartphones as the educational tool. Therefore a large research study on mobile HPC systems is needed to confirm the usefulness as the educational tool. However, the results are highly promising.

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